

**The effect of irrigation on barley root architecture, yield and  
water-use efficiency in vertic texture contrast soils**

By

**Marek Rudolf Matuszek**

BAppSci(Agr) (Hons)

University of Tasmania

Submitted in fulfilment of the requirements for the degree of Masters of Agricultural  
Science

School of Land and Food, University of

Tasmania, March 2017

## **Declaration**

I hereby declare that this thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Marek Rudolf Matuszek

This thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

Marek Rudolf Matuszek

## **Abstract**

Water availability is an ever increasing issue for agricultural production around Australia. Australia's south-eastern high-rainfall zones (annual rainfall between 500 and 900 mm) allow for extensive cropping. In Tasmania, this often requires supplemental irrigation to maximise yields. Texture contrast soils occupy 80% of southern Australian agricultural regions and can be difficult to irrigate due to hydraulic complexities, particularly with a vertic, clay subsoil.

This thesis assesses how strategic irrigation can be used to overcome the complexities of texture contrast soils to improve grain yield and water-use efficiency (WUE) of barley through maximising root depth and distribution. Detailed root spatial data and growth rates were used to present a method to improve the simulation of barley growth and development on texture-contrast soils in the high rainfall zone.

Barley (cv. Gairdner) was grown under waterlogged, optimal irrigation and rainfed conditions with five replicates on a texture contrast soil in southern Tasmania. Plants were sampled three times through the season for yield and yield components. Following harvest, 1 m<sup>2</sup> pits were excavated and root number, soil moisture and soil strength were measured on horizontal soil faces to a depth of 110 cm. Volumetric soil moisture was recorded in each treatment throughout the growing season with a Sentek EnviroSCAN to a depth of 110 cm. Soil, plant and weather data were collated to parameterise the crop simulation model APSIM for the calculation of WUE.

Increased root depth significantly improved grain yield and WUE. Maximum rooting depth was greatest under optimal irrigation and shallowest under rainfed conditions.

Increased root depth was associated with improved grain yield. Grain yield was greatest under optimal irrigation, followed by the waterlogging and rainfed conditions, respectively. Optimal irrigation had the greatest WUE. Even though the rainfed conditions lead to the poorest yield, WUE was greater than the crop subjected to waterlogged conditions.

Increasing the frequency and amount of irrigation led to waterlogging of the A horizon, which is a potential issue in texture contrast soils. The abrupt change in texture means there is a large contrast in the permeability of the two soil horizons. The low permeability of the B horizon and the low water holding capacity of the A horizon makes the soils very prone to waterlogging, particularly under irrigation. Although the soil in the waterlogged treatment had a lower penetration resistance, root depth was shallower than for the optimum treatment.

The default capacity of APSIM to simulate barley grown on Tasmanian vertic texture contrast soils was relatively poor and parameters such as yield and root growth were overestimated. This was addressed by revising the root exploration factor and root water extraction parameters of APSIM, based on detailed root density curves.

Strategic irrigation of barley improved grain yield, rooting depth and distribution in vertic, texture contrast soils. A better understanding of root-soil interactions can be used to develop more effective irrigation to increase yields and water-use efficiency of grain crops in these hydraulically complex soils.

## Public output

Matuszek, M (2010) The effect of irrigation on water-use efficiency and root growth of barley in texture contrast soils in Tasmania. 10 September 2010. Introductory Seminar (UTAS, School of Agricultural Science Seminar Series).

Matuszek, M (2010) Seaton field trial 2010. Field demonstration to growers in the Coal Valley Products Association on 15 December (in collaboration with UT00016).

Matuszek, M and Botwright Acuna, T and Parsons, D and Hardie, MA, “The effect of irrigation on barley root architecture, yield and water-use efficiency in vertic texture contrast soils”, *Irrigation 2011 - New Horizons, Fresh Ideas Conference*, 22-25 August 2011, Launceston, Tasmania (2011) [Non Refereed Conference Paper].

Matuszek, MR and Botwright Acuna, T and Parsons, D and Hardie, MA, ‘Root architecture of barley in texture contrast soils under irrigation’, Proceedings of the Rhizosphere 3 Conference, 25-30 September 2011, Perth, Western Australia (2011) [Conference Extract].

Matuszek, M (2012) The interaction between soil strength and water availability of texture contrast soils on above and below ground crop performance and WUE. Seminar (UTAS, School of Agricultural Science Seminar Series).

Matuszek, M (2012) The interaction between soil strength and water availability of texture contrast soils on above and below ground crop performance and WUE. Annual GRDC WUE meeting, 7-8 August, Hobart. In conjunction with UT00016 ‘Improved water-use efficiency of irrigated and rainfed farming systems in Tasmania’.

Matuszek, M (2015) Strategic irrigation, understanding root growth and waterlogging avoidance. Landmark mixed cropping information day on 07 August 2015, Latrobe. In conjunction with Landmark Ltd.

Matuszek, M (2015) Strategic irrigation and soil moisture monitoring in cereals. Southern Farming Systems field demonstration site on 27 November 2015, Hagley. In conjunction with Southern Farming Systems Tasmania.

## **Acknowledgements**

There are a large number of people that would sincerely like to thank in the completion of this thesis. This is the most enjoyable part of the whole thesis to write because I am able to express my gratitude to all those that have helped me over the course of this work and there are no references required because it's all from the bottom of my heart.

Firstly I would like to sincerely thank my supervisors, Tina Acuña, Marcus Hardie and David Parsons for their advice, support and patience throughout the project. Not only have they helped me in the completion of the thesis, but have played a major role in building my passion for my work and Tasmanian agriculture.

To my parents and family. I thank them for nurturing my curiosity that would result in me thinking, as I sat in a big dirty soil pit on a cold miserable day, looking at a mess of soil and roots, "this looks interesting". You don't often get a chance to show your appreciation to those you most love, but finishing a thesis will sure do it!

A great deal of thanks goes to my employers, Reuben and Kate Wells at Ag Logic for the patience and encouragement they have given me while completing my thesis. They have allowed me to focus the time and energy on it by reducing the temptation of being out in the field rather than at the desk. I am very lucky that I have been given the opportunity to begin my career in such a great environment that allows me to apply (and continue to expand) the concepts I have developed in this thesis to commercial agriculture.

To all the staff and fellow students at the School of Land and Food. Not only in helping with the thesis but also making the faculty a fantastic place to study and providing plenty of enjoyable distractions and memories.

Thank you to my funding body, the Grains Research and Development Corporation for allowing me to carry out my work and to be part of a larger project that holds many benefits for Australian agriculture. Also to the growers, in particular Ronald and Chris Gunn, whose paddocks, crops and irrigators I was constantly tinkering with.

And finally, I would like to thank my gorgeous, wonderful wife Emma. She has not known me without the thesis and I often took her support for granted. While there have been many ups and downs, Emma has been my one true constant with her unfaltering patience, understanding and support. An impending child is the perfect deadline and I cannot wait to begin the next stage of our lives by replacing the thesis with a beautiful daughter.

## **Preface**

This thesis documents the research undertaken between June 2009 and February 2016. This project was funded by Grains Research and Development Corporation, a research organisation responsible for planning, investing in and overseeing research and development to deliver improvements in production, sustainability and profitability across the Australian grains industry. The research is in preparation for future publication and the thesis structure has incorporated these manuscripts as research chapters. An introduction chapter provides background on the thesis topic and overall context for the research chapters. A general discussion expands the discussion presented in the research chapters.



## Contents

Declaration.....	i
Abstract.....	ii
Public output.....	iv
Acknowledgements .....	v
Preface .....	vii
Contents.....	viii
List of figures .....	x
List of tables .....	xiii
1.0 Chapter 1 – Introduction.....	1
1.1 Food and water supply .....	1
1.2 Tasmania’s climate.....	2
1.3 Barley .....	5
1.3.1 Tasmanian barley production .....	5
1.3.2 Barley growth stages .....	5
1.4 Water management.....	7
1.4.1 Water use, water-use efficiency and grain yield.....	7
1.4.2 French and Schultz (1984) WUE.....	8
1.4.3 Accounting for WUE losses .....	10
1.4.4 Crop simulation modelling .....	12
1.5 Soil characteristics and water use and grain yield.....	14
1.5.1 Water movement in texture contrast soils .....	18
1.5.2 Mechanical impedance and root growth.....	19
1.5.3 Soil structure.....	19
1.5.4 Soil type.....	19
1.5.5 Summary.....	20
1.5.6 Hypothesis .....	21
2.0 Chapter 2 – Water use of barley grown under irrigation on texture contrast soils .....	22
2.1 Introduction .....	22
2.2 Materials and methods .....	26
2.2.1 Experimental sites .....	26
2.2.2 Soil moisture monitoring .....	27
2.2.3 Experimental design .....	28
2.2.4 Plant sampling .....	29
2.2.5 Statistical analysis .....	30
2.2.6 WUE calculations .....	30
2.3 Results .....	31
2.3.1 Crop growth of barley at maturity in 2009/10.....	31
2.3.2 Vegetative development of barley in 2010/11.....	31
2.3.3 Yield and yield components of barley at maturity in 2010/2011 .....	32
2.3.4 Simulated water use and water-use efficiency using APSIM.....	33
2.4 Discussion .....	35
2.4.1 2009/10 field experiment.....	35
2.4.2 Yield and yield components .....	35
2.4.3 Lodging.....	37
2.4.4 Water-use efficiency .....	38
2.5 Conclusion.....	40
3.0 Chapter 3 – Root and soil interactions of barley on a texture contrast soil.....	41

3.1	Introduction .....	41
3.2	Materials and methods .....	43
3.2.1	Experimental design .....	43
3.2.2	Root and soil sampling .....	43
3.2.3	Soil profile analysis .....	43
3.2.4	Statistical analysis .....	45
3.3	Results .....	47
3.3.1	Treatment soil water content .....	47
3.3.2	Root depth and distribution .....	47
3.3.3	Soil moisture and penetration resistance .....	48
3.3.4	Crack number with depth .....	51
3.3.5	Root and soil interactions .....	51
3.3.6	Root and soil factor correlations.....	53
3.3.7	Recursive partitioning .....	55
3.4	Discussion .....	60
3.4.1	Root growth .....	60
3.4.2	Irrigation .....	62
3.5	Conclusion.....	64
4.0	Chapter 4 – Modification of APSIM parameters to improve simulation of barley growth in texture contrast soils.....	65
4.1	Introduction .....	65
4.2	Materials and methods .....	70
4.2.1	Experimental sites .....	70
4.2.2	Soil characterisation .....	70
4.2.3	Root sampling.....	71
4.2.4	2009/10 soil profile analysis.....	72
4.2.5	Saturated hydraulic conductivity .....	74
4.2.6	APSIM parameterisation .....	75
4.2.7	APSIM modelling- exploration factors .....	79
4.3	Results .....	81
4.3.1	2010/11 .....	81
4.3.1.1	Observed vs. simulated crop growth .....	81
4.3.1.2	Observed vs. predicted root growth over time .....	82
4.3.1.3	Observed vs. predicted leaf area index over time .....	85
4.3.1.4	Observed vs. predicted yield and yield components .....	87
4.3.2	APSIM validation with 2008/9 and 2009/10.....	89
4.3.2.1	Observed vs. predicted leaf area index.....	89
4.3.2.2	Observed vs. predicted yield and yield components .....	90
4.4	Discussion .....	93
4.4.1	APSIM soil/root parameterisation .....	94
4.4.2	Yield and crop simulations .....	97
4.5	Conclusion.....	99
5.0	General discussion.....	100
5.1.1	Overview .....	100
5.1.2	Irrigation scheduling.....	101
5.1.3	Crop simulation modelling of root growth.....	103
5.1.4	Future experiments .....	106
5.1.5	Conclusion.....	107
6.0	References .....	109

## List of figures

Figure 1-1. The projected change of stress on water resources throughout the world in 2025 with the continuation of current trends of population growth and agricultural practices (Alcamo et al. 2000). .....	1
Figure 1-2. Tasmania's annual average rainfall (a) and maximum temperature (b) from 1961 to 1990 (Source: Australian Bureau of Meteorology 2008) .....	4
Figure 1-3. The arbitrary line in this graph developed by French and Schultz (1984) demonstrates the linear relationship between potential yield and water-use for wheat. All experiments that fall below the line are therefore limited by factors such as environment, management practices or soil health (French and Schultz 1984b). .....	9
Figure 1-4. These graphs developed by Perry (1987), uses post-anthesis transpiration, vapour pressure deficit and changes in the ratios of evapotranspiration to simulate WUE. The first graph is quite similar to the F&S model of 20 kg/ha.mm when taking into account post-anthesis transpiration. The graph on the right factors in changes in evapotranspiration through crop development and demonstrated that water use is not proportional to yield. ....	12
Figure 1-5. The structure for the APSIM program. (Source: McCown. et al 1995) .....	13
Figure 1-6. Distribution of texture contrast soils in Australia (Chittleborough 1992). ....	14
Figure 1-7. Distribution of three dominant texture contrast soil orders in Tasmania, Kurosol, Chromosols and Sodosols (Cotching et al. 2009) .....	15
Figure 2-2. Experimental design overlapping EM38 mapping of the field site. Large dots represent pairs of sprinklers and the small dots represent the position of the EnviroSCAN tubes.....	29
Figure 3-1. Soil pit from which the soil profile analysis was conducted at the time of root count of the 2010/11 field trial and described using Isbell (2002). ....	45
Figure 3-2. 10 x 10 cm grid nomenclature used to assess the spatial influence of soil factors, treatment effects on root number in the recursive partitioning analysis.....	46
Figure 3-3. Soil moisture content taken from EnviroSCAN data of treatments to a depth of 110 cm during the irrigation period. The lower and upper edges of the box represent 25th and 75th percentiles, and the solid and dashed lines are the medians and means in each box. The 'error bars' indicates 10th and 90th percentiles.....	47
Figure 3-4. Effect of irrigation on root depth and distribution during the 2010/11 field season. ....	48

Figure 3-5. Penetration resistance of clay subsoil in relation to gravimetric soil moisture at harvest for all depths in (a) rainfed, (b) optimum and (c) waterlogged treatments. The penetrometer could not take readings over 4000 kPa (denoted by the empty circles), therefore  $R^2$  values are derived from readings under 4000 kPa only. The dotted line at 2000 kPa represents the level at which cereal roots are severely restricted (Hazelton and Murphy 2007).

.....50

Figure 3-6. Total number of grids containing a crack in the rainfed, optimum and waterlogged treatments at harvesting (a) and the number of grids containing a crack separated into dept in each of the treatments (b). ....51

Figure 3-7. Principle component analysis of soil moisture, soil strength, crack abundance and root number for all treatments selected at (a) 20, (b) 30, (c) 50 and (d) 70 cm.....52

Figure 3-8. Degree and direction of correlation between soil moisture, strength and cracks with root number in the (a) rainfed, (b) optimum and (c) waterlogged treatments verses depth. \* denotes a significance of  $p < 0.05$  between root number and the soil factor at that depth, \*\*  $p < 0.01$  and \*\*\* a significance of  $p < 0.001$ . ....54

Figure 3-9. Conditional inference regression tree indicating (a) the importance of root architecture, cracking, penetration resistance and irrigation treatments on root number for any target cell and (b) after the removal of treatment as a factor.....58

Figure 3-10. Conditional inference regression tree indicating (a) the importance of soil factors and irrigation treatments when Roo.AAv removed as a factor (b) Roo.AAv and treatment removed as a factor.....59

Figure 4-1. Diagrammatic representation of the APSIM framework (Keating et al. 2003b)..66

Figure 4-2. Soil pit from which the soil profile analysis was conducted after harvest of 2009/10 field trial and described using Isbell (2002). ....74

Figure 4-3. Modified Amoozegar and Warrick (1986) design used to derive hydraulic conductivity measurement for APSIM parameterisation.  $\Delta H$  denotes the total difference in head, A is the cross-sectional area, V is the total volume of the core, L is the length of the core and Q is the quantity of water collected. ....75

Figure 4-4. Comparison of observed and simulated APSIM root growth of rainfed, optimum and waterlogged treatments derived from simulations containing default KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, adapted KL parameters ( $KL_A$ ) and adapted KL ( $KL_A$ ) and XF ( $XF_A$ ) parameters.....84

Figure 4-5. Comparison of observed and simulated APSIM leaf area index (LAI) of rainfed, optimum and waterlogged treatments in season 2010/11 derived from simulations containing default KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, adapted KL parameters ( $KL_R$ ) and adapted KL ( $KL_R$ ) and XF ( $XF_R$ ) parameters. ....86

Figure 4-6. Comparison of observed and simulated APSIM yield (a), grain number (b) and grain weight (c) derived from simulations containing default APSIM KL (KL<sub>D</sub>) and XF (XF<sub>D</sub>) parameters, adapted KL parameters (KL<sub>A</sub>) and adapted KL (KL<sub>A</sub>) and XF (XF<sub>A</sub>) parameters. Error bars for observed grain number and weight represent  $\pm 1$  standard error..... 88

Figure 4-7. Comparison of observed and simulated APSIM leaf area index (LAI) of seasons a) 2008/09 and b) 2009/10 from simulations containing default KL (KL<sub>D</sub>) and XF (XF<sub>D</sub>) parameters, revised KL parameters (KL<sub>A</sub>) and revised KL (KL<sub>A</sub>) and XF (XF<sub>A</sub>) parameters. .... 90

Figure 4-8. Comparison of observed and simulated APSIM yield (a), grain number (b) and grain weight (c) derived from simulations containing default APSIM KL (KL<sub>D</sub>) and XF (XF<sub>D</sub>) parameters, revised KL parameters (KL<sub>A</sub>) and revised KL (KL<sub>A</sub>) and XF (XF<sub>A</sub>) parameters. Error bars for observed grain number and weight represent  $\pm 1$  standard error..... 92

Figure 5-1. A conceptual hypothesis on the dynamic relationship between shrink swell soils and root growth..... 102

Figure 5-2. Yield of 50 year barley simulations from 1960 to 2010 in the Cambridge region containing default KL and XF parameters and adjusted parameterisations as pretested in the 2010/11, chapter 4. Simulations involved rainfed crops, early season irrigation, which consisted of irrigating when extractable soil water dropped below 140 mm between Zadok stage 1 and 45 and the late season simulation between Zadok stage 45 and 70..... 105

## List of tables

Table 2-1. Irrigation and rainfall amounts (mm) from the 2009/10 and 2010/11 field experiments.....	28
Table 2-2. Effect of irrigation on plant growth and yield at maturity in the 2009/10 season. 31	
Table 2-3. Effect of irrigation on plant growth and development at anthesis in the 2010/11 experiment (88 DAS). ....	32
Table 2-4. Effect of irrigation on crop growth, yield, yield components and lodging at maturity.....	33
Table 2-5. WUE calculation of irrigation treatments using plant water-use and water loss data derived from APSIM simulations. All forms of water loss from the soil profile were measured in mm. ....	34
Table 4-1. Initial gravitational soil moisture (SM), nitrate (NO <sub>3</sub> ), ammonium (NH <sub>4</sub> ) and total organic carbon (OC) from data collected from the field site, used to parameterise APSIM... 77	
Table 4-2. Soil data from lab testing across all treatments as entered into APSIM simulations, including bulk density (BD), volumetric soil water of air dried samples (Air dry), samples pressurised to -1500 kPa (LL15), samples drained to -10 kPa (DUL) and saturation samples. APSIM derived data includes barley lower limit (Barley LL) and plant available water capacity (PAWC). Electrical conductivity and (EC) and pH were derived from start of season sampling. ....	78
Table 4-3. APSIM default values of water extraction (KL <sub>D</sub> ) and root exploration (XF <sub>D</sub> ) and adapted values (KL <sub>A</sub> /XF <sub>A</sub> ) used for adapted APSIM simulations for each treatment. All KL <sub>A</sub> values are represented as a fraction of the root count taken at the optimum treatment at 25-30 cm from the 2010/11 field experiment. All XF <sub>A</sub> values are a fraction of the individual treatments maximum root count. ....	80
Table 4-4. Comparison of observed and default APSIM simulated phenology, leaf area index (LAI), yield and components of yield. The simulated/observed ratio is included to evaluate initial model performance.....	82
Table 5-1. Median values of WUE from 50 year barley simulations from 1960 to 2010 in the Cambridge region containing default KL and XF parameters and adjusted parameterisations as pretested in the 2010/11 trial, chapter 4. Simulations involved rainfed crops, early season irrigation, which consisted of irrigating when extractable soil water dropped below 140 mm between Zadok stage 1 and 45 and the late season simulation between Zadok stage 45 and 70. Simulation outputs included plant water uptake and water loss from the cropping system. Day of soil moisture being greater than the drained upper limit (DUL) occurring in the soil layer above the B horizon was used to determine the prevalence of perched waterlogging.....	106

## 1.0 Chapter 1 – Introduction

### 1.1 Food and water supply

World population is rapidly rising, leading increased poverty and starvation in under developed countries (Döös 1994). The World Development Report (2008) states that agriculture can make considerable contributions to alleviate these issues. However, arable land is slowly declining and therefore if agriculture is to meet the nutritional demand of a growing population, there must be considerable investment and research into increasing production with fewer resources. Water is one of these limiting resources and its availability is in steady decline in many agricultural regions of the world (Figure 1-1). Factors influencing water availability are a growing population, increased urbanisation and higher consumption (particularly in developing nations) and climate change (Bates *et al.* 2008).

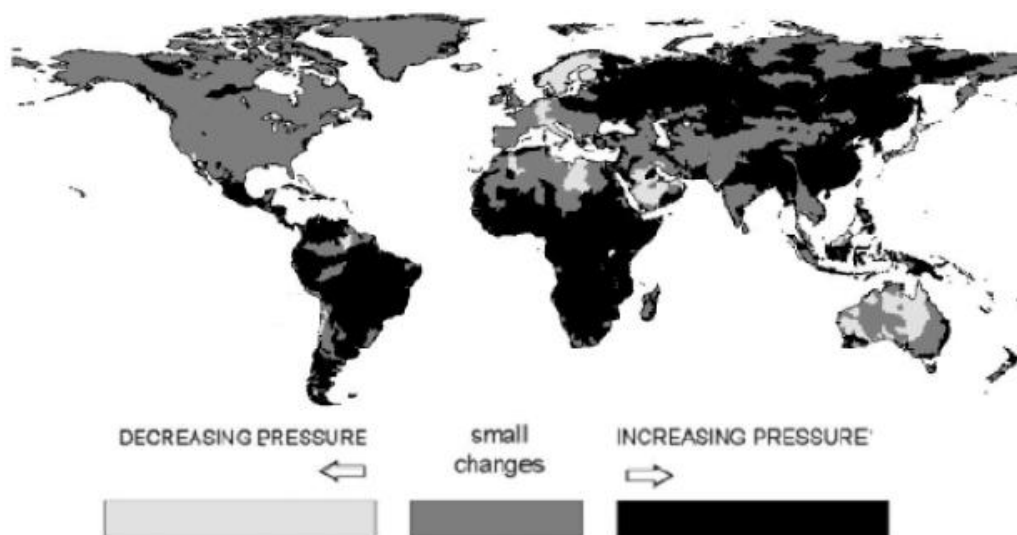


Figure 1-1. The projected change of stress on water resources throughout the world in 2025 with the continuation of current trends of population growth and agricultural practices (Alcamo *et al.* 2000).

Like the rest of the world, arable land in Australia is steadily decreasing due to salinity, acidity, soil degradation, water availability and to a lesser extent urban encroachment (Eadie and Stone 2012). Some of Australia's agricultural production relies heavily on irrigation. Agriculture consumes 70% of Australia's water resources, three quarters of which occurs in the Murray Darling Basin (Chartres and Williams 2006).

With the Murray Darling Basin struggling to increase production due to environmental constraints such as salinity (Beal 1993), Tasmania has the opportunity to capitalise on its available water resources and quality farming land (National Water Commission 2013). The development of irrigation schemes by the State and Federal Governments and greater access to water across the state has increased the capacity for irrigated agriculture. However, the introduction of irrigation in many of these previously unirrigated regions requires careful planning and use of water to maintain and maximise sustainable agricultural production.

## **1.2 Tasmania's climate**

Tasmania has a maritime climate, with four distinct seasons. The state generally experiences mild summers with an average maximum temperature of 21°C and cool winters with an average maximum temperature of 12°C. Tasmania is situated in the roaring forties wind system, which causes large variations in both temperature and rainfall around the State (Figure 1-2) (BOM 2008). Altitude also has a large effect on local climate, which ranges from alpine to coastal areas. Rainfall is generally winter dominant with a majority of the rainfall falling on the mountainous west coast, which impedes rainfall in the Midlands and Derwent Valley (Figure 1-2a). The rainfall in the major cropping districts of the north and north east are influenced by low pressure systems off the southern



coast of Australian mainland, which bring much of their winter rain (Pook 2001). Tasmanian cereal cropping regions are highly variable in rainfall quantity and distribution (Figure 1-2a). Northern Tasmanian regions receive in excess of 900 mm annually whereas south-eastern areas typically average 600 mm per year (BOM 2008).

Tasmania's mild climate contributes to the high yield potential of grain crops (Botwright Acuña *et al.* 2011). However, grain yield in the central and southern midlands can be limited by a combination of cold temperatures in winter, and low rainfall in the spring and summer. Spring also has relatively high incidence of frost, which may impact on grain set if these conditions coincide with flowering (Dean and Mendham 2001). Frosts are also common in these regions and can also have a severe impact on crops particularly as they can occur as late as mid-November (Dean 2001).

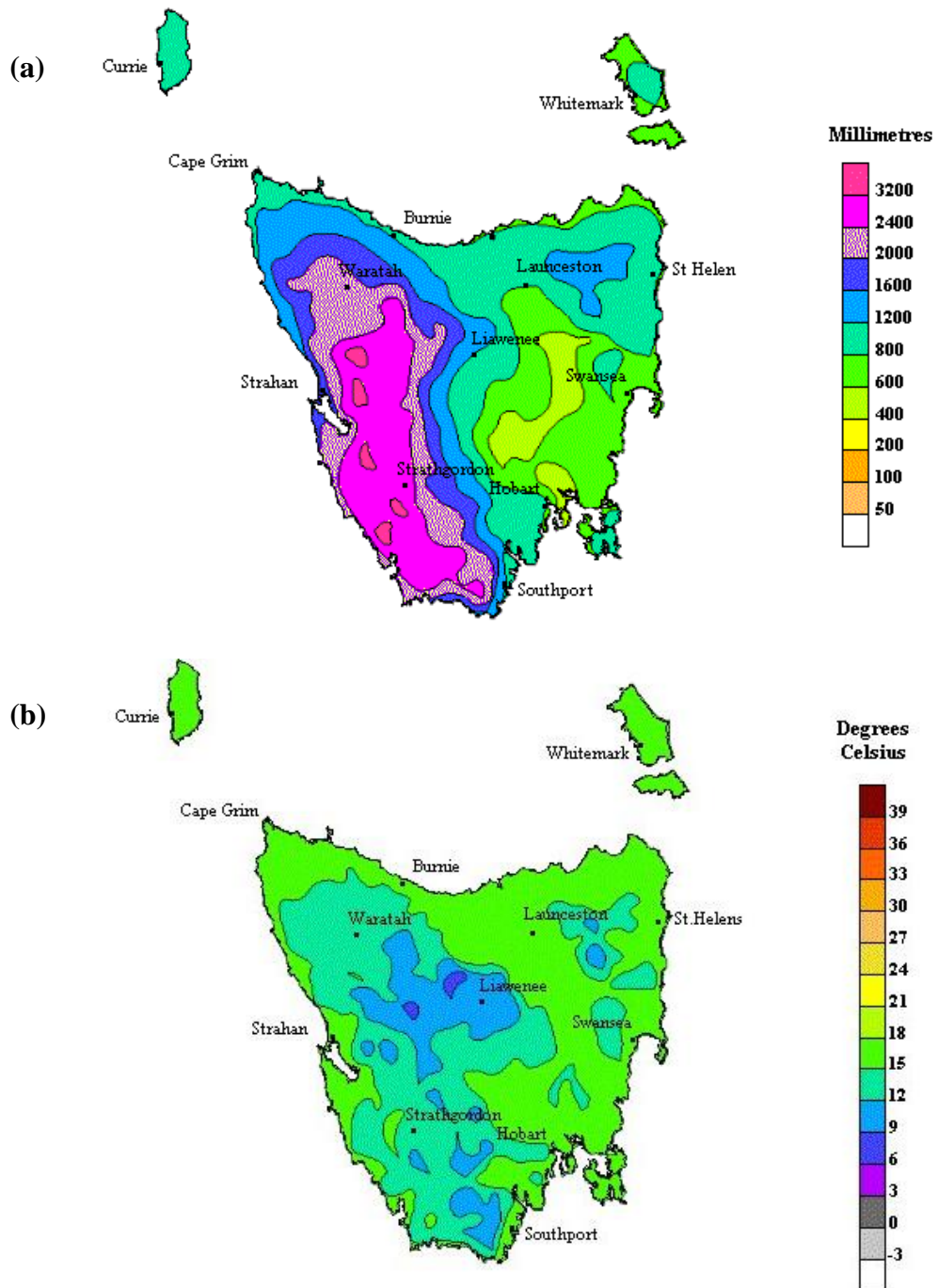


Figure 1-2. Tasmania's annual average rainfall (a) and maximum temperature (b) from 1961 to 1990 (Source: Australian Bureau of Meteorology 2008)

## **1.3 Barley**

### *1.3.1 Tasmanian barley production*

Barley is the most widely grown broad acre crop in Tasmania with total annual production averaging roughly 25,000 tonnes between 2001 and 2005 (ABS 2008). It is predominantly grown in the drier areas of the state, returning yields between 2.5 and 3.5 t/ha (ABS 2008). It is also grown in regions such as the North West Coast as a rotation crop with vegetables. Most of the barley crops around the state are sown from autumn through to winter with spring sowing possible under irrigation. Yields fluctuate from year to year as Tasmanian cereal production is very dependent on seasonal climatic conditions, particularly dry-land crops. Irrigation mitigates unpredictable rainfall patterns and is often required to produce high quality malting barley for beer or whisky. Franklin and Gairdner are the two major varieties grown in Tasmania as they are able to satisfy the stringent grain protein level requirements for the local brewing industry (DPIW 2008). Cereal production in Tasmania is small scale compared with the mainland and demand different management practices. Irrigation of cereals in mainland Australia is not a widespread practice, however it is becoming more common in Tasmania as a means of increasing yields and improving water-use efficiency (WUE) (DPIW 2008).

### *1.3.2 Barley growth stages*

The growth stages of barley differ slightly from wheat as flowering occurs during head emergence from the boot, however the growth stages are still quantified using the Zadoks growth scale (Zadoks *et al.* 1974). The Zadoks growth scale extends from 0 to 99 detailing a specific stage of growth.

Germination requires a minimum ground temperature of 2°C along with adequate soil moisture to occur. During germination, the primary root emerges and develops lateral roots to take in water and nutrients. Once the shoot leaf emerges, the plant moves to the establishment phase. The first true leaf appears and after about three leaves, depending on cultivar, the plant begins to tiller. Tiller emergence and number are very responsive to environmental conditions and also depend on the vigour of the cultivar (Miralles and Richards 2000). Tillers emerge over roughly a two week period and some tillers start to die approximately one month after emergence, depending on how favourable growing conditions are. At this point of development, the plant apex is below the soil surface. Once tillering has ceased, the internodes begin to elongate and the developing head grows rapidly towards the boot. Just prior to head emergence, flowering and pollination takes place. Any environmental stresses at this time effects the number of kernels in the head (Aspinall *et al.* 1964).

Once pollination has taken place the head emerges and the kernels start to develop. Nutrients or water stress affects kernel size in these early stages of development (Aspinall *et al.* 1964). During later kernel development, these stresses may reduce cell division within the grain, which reduces the ability for the gain to store starch. Towards the end of kernel development, the kernels rapidly lose water until they have a moisture content of roughly 30 - 40%. The grains will not accumulate any more dry matter after this and final yield can be established. For the crop to be ready for harvest the grains must reach a moisture content of between 13 and 14% (Anderson *et al.* 2002).

## **1.4 Water management**

Water availability is becoming an ever increasing issue in agricultural production (Chartres and Williams 2006). To fully maximise the effectiveness that these advances have on agricultural production, the available water must be utilised as efficiently as possible. Therefore farmers need to improve traditional irrigation scheduling techniques including the common practice of only visually checking the topsoil, in order to operate in an economical and environmentally sustainable manner. As a result, WUE is an increasingly important aspect in improving the viability of agricultural practices and to fully maximise the effect that these proposed developments will have on agriculture throughout the state.

There is also increased competition for water allocation for agriculture, domestic, industrial use and environmental flows (DPIWE 2004). Water sourced for agriculture from catchments, rivers and dams is limited by the environmental health of the water source. More focus on environmental sustainability, results in less readily available water for agricultural production (DPIWE 2004). Domestic households and industrial water use has always been a large consumer and competitor for available water. The issue of decreasing water availability has led to a stronger focus on supplying reuse water from domestic systems to agriculture. This is an important step towards reducing grower's uncertainty in climatic variability and increasing WUE.

### **1.4.1 *Water use, water-use efficiency and grain yield***

Water-use efficiency has been defined as the measurement of yield or biomass per unit of crop water use (Sinclair *et al.* 1984). There have been many detailed studies regarding WUE, particularly grain yield in relation to growing season rainfall dating back to

Richardson in 1923 (Sadras and Angus 2006a). These reports demonstrated the potential yields that cereals could attain in particular environments by taking into account growing season rainfall. Based on water-use of the crop and growing season rainfall, a system defining WUE was developed in the form of kg/ha.mm (French and Schultz 1984b).

#### 1.4.2 *French and Schultz (1984) WUE*

It was not until French and Schultz (1984) (F&S) that an extensive study was undertaken in order to quantify the relationship between yield and water-use as well as a simple method for predicting potential yield based on total seasonal rainfall (Angus and Herwaarden 2001b).

Through data obtained from 64 sites between 1964 and 1975, French and Schultz (1984) developed a graph (Figure 1-3), which related yield of wheat crops in South Australia with seasonal rainfall in excess of irrigation. The dotted line through the upper bound points represents the potential yield of the crop in relation to water use. The line intersects the x-axis at 110 mm, which equates to soil evaporation (French and Schultz 1984b). This model has been widely used in southern mainland Australia as a simple and effective method for simulating potential yield in response to available rainfall (Robertson and Kirkenggaard 2005).

There are several drawbacks to the (F&S) approach, particularly in relation to its potential use in Tasmania. It does not take into consideration the distribution of the rainfall or the amount of water the crop has used (Perry 1987b). It also assumes that runoff and deep drainage are negligible (Robertson and Kirkenggaard 2005). This then raises the question of

what period of rainfall should be included to accurately simulate actual plant water uptake. French and Schultz (1984) postulated that a majority of the water used by the crop falls within the cropping season with some access to stored soil moisture. They then concluded that 65% of variation in grain yield in their experiments was associated with rainfall period April to October (growing season typically June to December), which therefore includes pre-sowing rainfall and discounts post-anthesis rainfall. However, Sief and Pederson (1978) found that in their experiments, 86% of variation in yield was due to rainfall which occurred from three weeks before anthesis to two weeks after. These conflicting reports show that variations between seasons, such as rainfall and temperature as well as regional differences, such as soil type and management practices can influence how the crop utilises water. Therefore it is important to be able to quantify the yield and water-use of the crop to gain a further understanding of what yields can be achieved based on water availability (Robertson and Kirkegaard 2005).

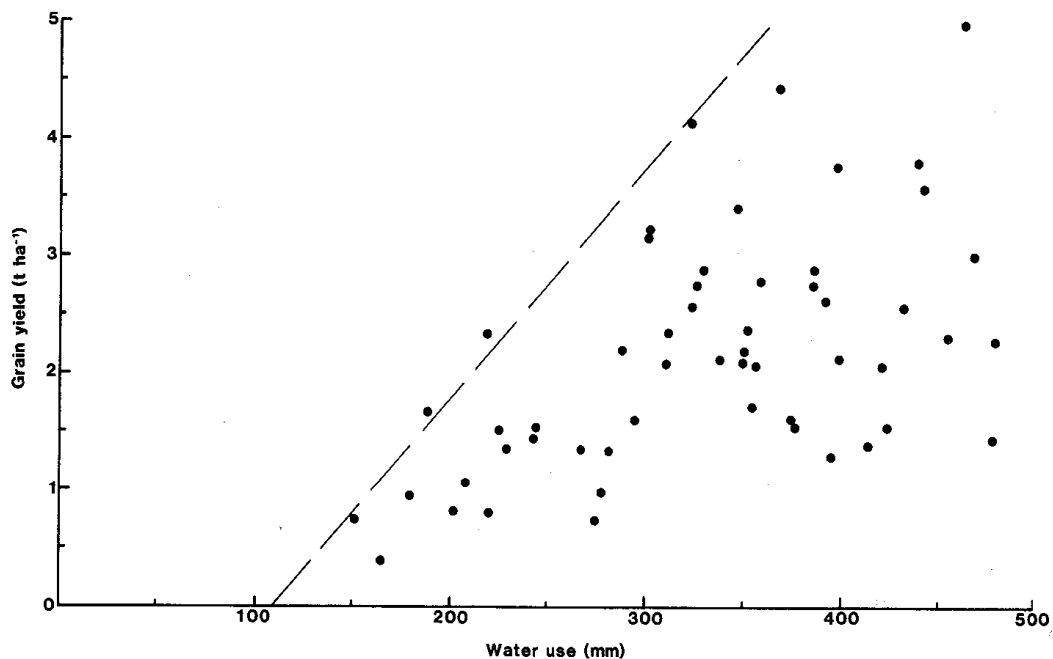


Figure 1-3. The arbitrary line in this graph developed by French and Schultz (1984) demonstrates the linear relationship between potential yield and water-use for wheat. All experiments that fall below the line are therefore limited by factors such as environment, management practices or soil health (French and Schultz 1984b).

#### 1.4.3 *Accounting for WUE losses*

Perry (1987a) took the F&S model a step further in order to segregate the direct evaporation of 100 mm into surface evaporation or transpiration. Also adding deep drainage and surface runoff as forms of water loss, the following equation was developed.

$$SW1 + P = RO + D + (SE + T) + SW2$$

WUE measurements consisted of initial (SW1) and final (SW2) soil moisture, rainfall (P), soil surface evaporation (SE), transpiration by the crop (T), surface runoff (RO) and deep drainage (D). In this equation, surface evaporation and transpiration are often treated as one value, evapotranspiration (Perry 1987b).

Perry (1987b) focused on evapotranspiration at the plant level in order to modify the F&S model to better understand the variations of WUE in different environments. This was carried out by studying CO<sub>2</sub> assimilation for specific plant species, which allowed vapour pressure deficits to be calculated (Angus and Herwaarden 2001b). Vapour pressure deficit (VDP) takes into account the daily changes in temperature and humidity between environments. However, to be useful in a WUE equation, the surface evaporation and transpiration components of evapotranspiration need to be determined (Perry 1987b). The ratio of surface evaporation and transpiration is not constant through the growing season, as canopy cover increases as the crop matures. Therefore, the method of measuring surface evaporation is divided into two techniques. Evaporation from bare soil is estimated through pan evaporation whereas evaporation from soil under canopy is proportional to the



radiant energy reaching the surface (Perry 1987b). In order to develop a model that compared water use and grain yield, timing of season rainfall with regard to grain yield had to be determined (Perry 1987b). Through experiments in Western Australia, Perry (1987b) concluded that the amount of water used post-anthesis, although much less than pre-anthesis rainfall is just as important for grain yield. From the data and VDP calculations, Perry (1987b) estimated that 30% of total transpiration related to grain yield took place after anthesis (Angus and Herwaarden 2001b).

With the data that Perry (1987b) calculated, they developed two models (Figure 1-4) that were an extension on the F&S WUE model. The model on the left is very similar to the original F&S version yet the x-axis intersect is less as there is more focus on post-anthesis transpiration. The three lines simulate different vapour pressure deficits and so demonstrate how climate causes limitations. The model on the right is a more realistic representation of water use compared with yield. It takes into account the development of the crop in regards to water loss through both surface evaporation and transpiration. This then suggest that WUE decreases with increasing water supply (Perry 1987b).

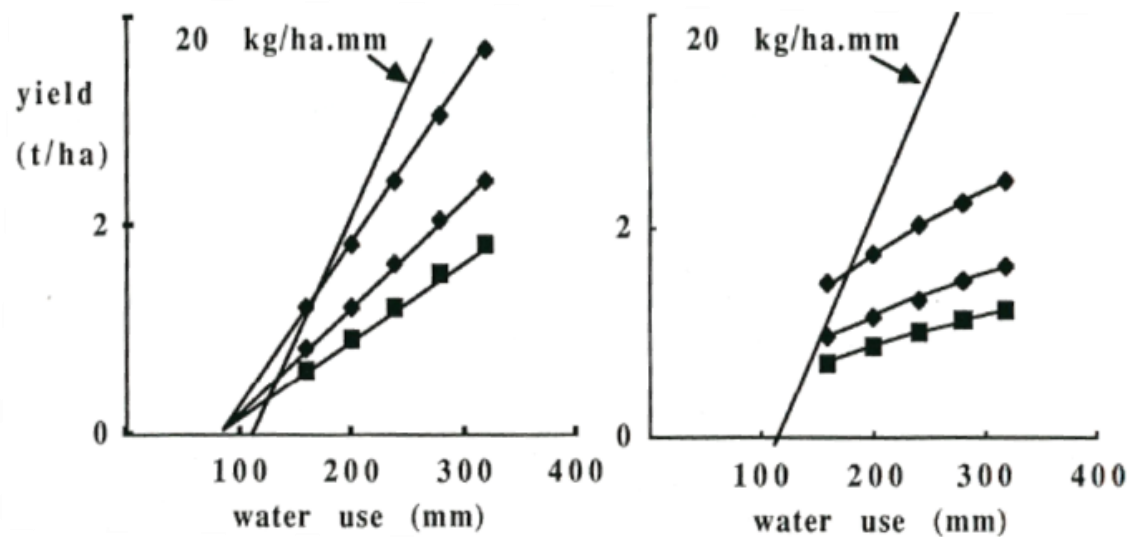


Figure 1-4. These graphs developed by Perry (1987), uses post-anthesis transpiration, vapour pressure deficit and changes in the ratios of evapotranspiration to simulate WUE. The first graph is quite similar to the F&S model of 20 kg/ha.mm when taking into account post-anthesis transpiration. The graph on the right factors in changes in evapotranspiration through crop development and demonstrated that water use is not proportional to yield.

#### 1.4.4 Crop simulation modelling

While crop models exist such as CropSyst (Stockle *et al.* 1994) and SGS/DairyMod/EcoMod (Johnson *et al.* 2008), this review focuses on APSIM as its application is commonly used in many Australian farming systems (Keating *et al.* 2003b). The APSIM (Agricultural Production System Simulator) model was designed for farm system analysis and improving decision making (McCown *et al.* 1995). The model is centred on the soil and simulates the growth, development and yield of a range of crops in response to climate, soil and management factors. APSIM can be used to determine the WUE of a crop by simulating the key elements of the cropping system, water balance and the grain yield as identified by Perry (1987) above.

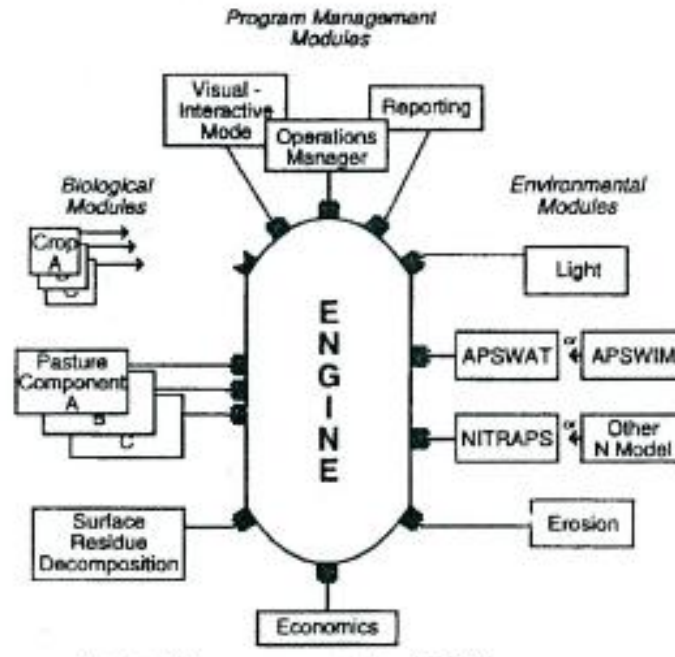


Figure 1-5. The structure for the APSIM program. (Source: McCown. et al 1995)

The model can simulate soil evaporation more accurately than (French and Schultz 1984a). It can also simulate the transpiration of the crop depending on the climate and growth stage as Perry (1987b) did in Figure 1-4. Water loss through surface runoff and deep drainage and the inefficiencies of an irrigation system can be quantified to determine how much water becomes available to the crop.

There are a number of limitations to the APSIM model. Firstly, the ability to simulate a cropping system is limited by the available site information (Carberry *et al.* 1995). It does not accurately simulate water movement for all soils which may cause miscalculations in water loss. APSIM assumes perfect management practices, and so does not take into account biological limitations including weed competition, pests and disease. It also does not fully take into account waterlogging or extreme weather events that may cause loss of yield such as seed shedding or lodging (Keating *et al.* 2003a).

### 1.5 Soil characteristics and water use and grain yield

Texture contrast soils (duplex soils) occupy approximately 20% of Australia (Chittleborough 1992) and roughly 80% of Southern Australian agricultural regions (Stevens *et al.* 1999). Texture contrast soils are defined as having a sharp contrast between the surface and subsoil layers. The subsoil layer (B horizon) is 1.5 times finer in texture than the surface layer (A horizon) and the boundary is within 10 cm or less to be considered a texture contrast soil (Isbell 2002; Northcote 1979). Textures of the two layers vary from a sands to clay loams in the upper soil layer and light to heavy clays in the subsoil layers (Tennant *et al.* 1992)



Figure 1-6. Distribution of texture contrast soils in Australia (Chittleborough 1992).

Texture contrast soils, which include Kurosols, Chromosols and Sodosols, account for only 16.5% of Tasmania's soil types however sustain nearly one-third of the State's

modified pastures and cropping (Cotching *et al.* 2009). Kurosols are the most dominant of the texture contrast soils in Tasmania (9.8%) and occur mostly throughout the State's east. The main characteristic that classifies these soils is their strongly acid upper B horizon (Isbell 2002). A bleached A2 layer between the textural contrast of the A and B horizons is also common (Cotching *et al.* 2009). Kurosols are the second most cropped soil in the State. Chromosols have the same texture-contrast feature as Kurosols, however they differ through higher pH values due to reduced leaching, as they are located in the lower rainfall zones. They only make up 5% of Tasmania's soil and are mostly used for dryland grazing (Cotching *et al.* 2009). Sodosols are similar to Kurosols except that their upper B horizon is not strongly acidic (Isbell 2002). Doyle and Habraken (1993), estimated Sodosols to occupy up to 23% of arable soil in Tasmania, however re-assessment of the Soil Orders by Cotching *et al.* (2009) reclassified them as Kurosols. Therefore Sodosols make up only a minor Soil Order in the State (1.6%).

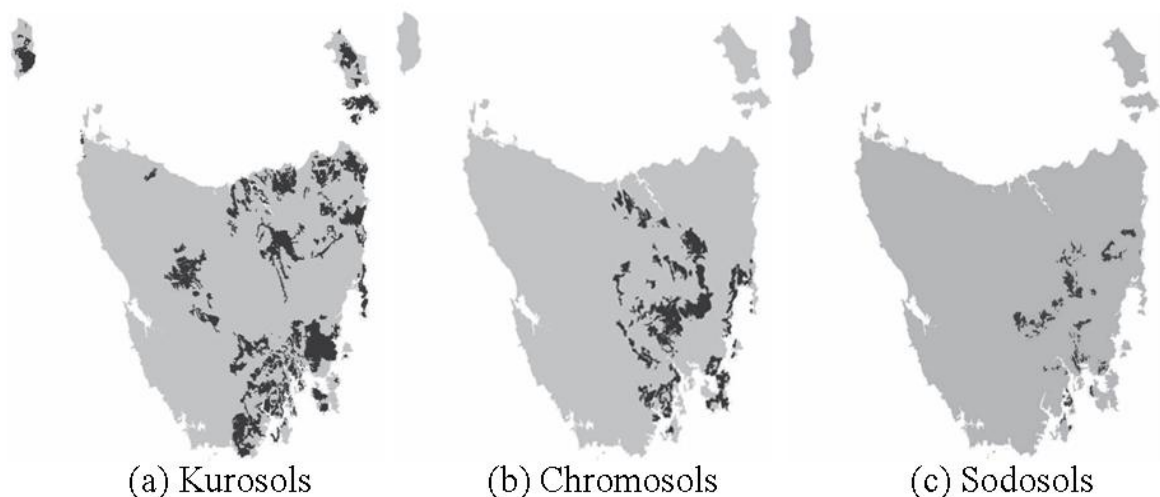


Figure 1-7. Distribution of three dominant texture contrast soil orders in Tasmania, Kurosols, Chromosols and Sodosols (Cotching *et al.* 2009)

The difficulties of cropping texture contrast soils have been well documented (Gardner *et al.* 1992; Anderson *et al.* 1992; Turner 1992; Edwards 1992) particularly yield variation within a paddock (Turner 1992). However, when appropriately managed, they have demonstrated to be no less productive compared with many other soils (Anderson *et al.* 1992). The strong texture-contrast characteristic is the major feature of these soils that make them difficult to manage. The abrupt change in texture also means there is a large contrast in the permeability of the two soil horizons (Tennant *et al.* 1992). The low permeability of the B horizon and the low water holding capacity of the A horizon, makes the soils very prone to saturation, commonly referred to as waterlogging. Waterlogged soils during establishment reduce plant growth and lead to weaker and shallower root systems, restricting their development deeper into the clay subsoil (Edwards 1992; Gardner *et al.* 1992). Plants that have a shallow root system cannot access available water at depth towards the end of the growing season. This is exacerbated in many cropping areas by a winter dominant rainfall pattern and therefore crops can be under waterlog and moisture stress within a number of weeks (Turner 1992).

Heterogeneity of water and nutrients are a common feature in texture contrast soils, which is the major cause for variation in plant growth within a paddock (Robson *et al.* 1992; Turner 1992). This has a profound effect on the distribution of roots throughout the profile and although studies have been carried out determining root and shoot response, it is unclear how total yield is affected (Robson *et al.* 1992).

The growth of barley roots in soils that have no structural impedance on root growth is highly dependent on the moisture of the soil. Roots penetration will continue through the growing season if the soil is above permanent wilting point, which is the point of minimal

soil moisture at which a plant cannot recover its turgidity (Salim *et al.* 1965). In soils such as deep sand or light loams, barley roots have been shown to penetrate to depths of up to 2 metres (Kirkegaard and Lilley 2007). This has shown to be advantageous by allowing it to utilise water otherwise unavailable to the plant (Hamblin and Tennant 1987; Siddique *et al.* 1990). However, it has been demonstrated in texture contrast soils, cereal varieties with deeper rooting systems do not significantly increase water uptake or grain yield due to the hard clay layer that restricts root growth (Belford *et al.* 1992; Dracup *et al.* 1992; Gregory *et al.* 1992; Siddique *et al.* 1990). Much of the root system is often confined to the sandy topsoil typical of texture contrast soils.

Many of these studies are carried out in cropping regions in the low to medium rainfall zone, which are subjected to shorter cropping seasons. As the clay layer becomes wetter, the penetration resistance decreases (Gracia *et al.* 2012), which may mean that high rainfall zones may be more favourable to root penetration in these layers due to the higher winter rainfall and therefore higher soil moisture. A longer growing season also gives the roots more time to explore the soil profile yet it also means that the plant has more time to extract the soil moisture. We hypothesise this water may then become available later in the season during post-anthesis, when water is important for grain filling. However, it is important for these roots to actually access and take up a large proportion of this water as roots can consume as much as twice the amount of resources to produce the same weight of above ground matter (Passioura 1983). If the roots are able to take up a majority of this water deeper in the profile it may reduce the reliance of irrigation after anthesis to achieve adequate grain fill.

Due to the high heterogeneity and spatial variability of the B horizon in texture contrast soils, it is difficult to understand root growth and distribution. Root growth and wetting fronts are highly variable and are often restricted to preferential pathways such as cracks, sand in-fills and biological pores (Belford *et al.* 1992; Dracup *et al.* 1992). These pathways have shown to assist roots in reaching depths deeper than one meter, yet their impact on leaving water unavailable to plants is unknown as it is not clear whether the roots can then access the surrounding soil matrix. There may be a relatively large mass of roots in these pathways at depth, however their effectiveness is reduced when clumped together (White and Kirkegaard 2010).

It is advantageous for cereals in deep sandy soils to have a deeper root system, which means water deeper in the profile available to the plant, especially post-anthesis. However, in texture contrast soils, such as in Tasmania, the clay layer acts as a barrier to the root system, preventing them from fully exploring deeper in the profile. This then raises the question of what type of root development is best for maximising WUE of the crop. How much of the B horizon can the root explore and therefore make water available, as most of roots are restricted to preferential pathways as is the water.

#### 1.5.1 *Water movement in texture contrast soils*

Utilization of stored soil water is dependent on the root growth and development of the crop. Water stored in the upper horizon is vital for establishment. However, as the season progresses and the plant roots grow deeper into the profile, sub-soil water becomes important in later development of the crop. Water used post-anthesis, although much less than pre-anthesis, is just as important for grain fill in cereals (Perry 1987a).



### 1.5.2 *Mechanical impedance and root growth*

Understanding the relationship and interaction between mechanical impedance of root growth, soil moisture and soil strength is an important aspect in increasing WUE and drought resistance in agricultural systems (Whitmore and Whalley 2009). However there are other plant and soil factors that also affect the ability to quantify their impact. These include soil type, structure, porosity, matric potential as well as plant responses such as shoot to root signalling (MacEwan *et al.* 2010; Whitmore and Whalley 2009).

### 1.5.3 *Soil structure*

Soil structure has many different effects on plants, the most notable being root development (Passioura 1991). More friable soils are conducive to rapid root growth. This is due to such soils generally having weaker soil strength than more compact soils and larger numbers of continuous pores, which travel deeper into the profile (Passioura 1991; Whitmore and Whalley 2009). These pores may be very small in diameter (<0.6 mm) however they can account for up to 70% of the roots in the soil (Zobel 2005). Soil texture is an important factor in determining the number of transmission pores. Light sands and sandy loams have a much higher proportion of pores, which are more easily accessible to roots than soils with a higher percentage of clay (Whitmore and Whalley 2009).

### 1.5.4 *Soil type*

Soils with high clay compositions may have a very low volume of pores at saturation (Whitmore and Whalley 2009) however, some clay soils have a shrink-swell characteristic

that causes cracks to form as the soil dries out (MacEwan *et al.* 2010). This form of macropore may allow roots to penetrate deeper into the profile however, they are a more complex type of macropore than biopores (Passioura 1991). Biopores, macropores created by animals and plants, are present regardless of the soil moisture content. Because crack formation is dependent on soil moisture, their occurrence and extent of cracking constantly varies. Therefore roots may not be able to access these cracks because the surrounding soil is too dry and hard for roots to penetrate (White and Kirkegaard 2010).

Although macropores aid root extension deeper into the profile, roots tend to clump together and this has been shown to reduce the effectiveness of water and nutrient uptake (Passioura 1991). However, in vertic soils, cracks are also a pathway for preferential water flow (Hardie *et al.* 2012). Therefore, although roots may be concentrated in these cracks, they receive moisture during rainfall or irrigation. A majority of this water will flow rapidly down the crack however some of it could permeate the crack walls and be available for plant uptake. This may also reduce soil strength in the crack walls and allow for roots to radiate into the bulk soil and increase rooting distribution.

#### 1.5.5 *Summary*

In texture contrast soils there are a number of physical subsoil constraints to cropping, specifically regarding root growth. These include water availability, soil aeration and mechanical impedance due to soil strength. These are all affected by the texture of the soil, its bulk density, soil water content and porosity (MacEwan *et al.* 2010).

Using irrigation as a means of aiding rooting depth is a dynamic process and it not fully understood (Whalley *et al.* 2006). When a plant is in a dry environment it will exert resources into growing roots into the soil looking for water. However, in texture contrast soils, the strength of the clay subsoil increases as it dries. The soil then reaches a point when roots cannot penetrate through the subsoil as it becomes too hard. Therefore the roots may not sufficiently reach water that is stored deeper in the profile, which has shown to have a large impact on grain yield and WUE (Kirkegaard *et al.* 2007). Conversely, when the soil is wet, particularly the upper layers, roots may not grow to access water deeper in the profile. Moisture levels may be sufficient for the crop growth at that particular stage of development however, wet soils have a lower penetration resistance and therefore this is the ideal time for roots to extend deeper into the profile. However, it is important to find a balance where the crop is forced into root exploration without the onset of high penetration resistance in the soil. This is where irrigation, particularly earlier in the growing season, may be used as a tool to influence root growth by increasing soil water availability later in the season as well as provide sufficient amounts of water for successful crop development.

#### 1.5.6 Hypothesis

- Can strategic irrigation be used to improve yield and WUE of barley crops by increasing root exploration in vertic texture contrast soils?
- What physical factors in a vertic texture contrast soil have the greatest influence on barley root growth and architecture?
- Can APSIM be used to accurately simulate crop growth and yield of barley on vertic texture contrast soils in a Tasmanian climate? If not, what are factors that limit the models accuracy?

## **2.0 Chapter 2 – Water use of barley grown under irrigation on texture contrast soils**

### **2.1 Introduction**

Australia's south-eastern rainfall zones are separated into low (annual rainfall between 300 and 510 mm) (Anderson and Garlinge 2000) and high-rainfall zones (annual rainfall between 500 and 900 mm) (Zhang *et al.* 2005). Tasmania has a slight winter dominant rainfall pattern consisting of cool, wet winters and mild, dry summers. While many parts of Tasmania's cropping regions are considered high rainfall zones (HRZ), northern areas receive annual rainfall greater than 900 mm (ABS 2004). In contrast, other parts of the State experience annual rainfalls consistent with low rainfall zones (LRZ) (ABS 2004). These regions often require supplemental irrigation to carry crops through to maturity and/or maximise yields.

Barley is the most widely grown broad acre crop in Tasmania, with total annual production of 28,000 tonnes over 9,500 hectares (Spragg 2014). It is predominantly grown in the drier areas of the state (Russell and Mendham 1985b). Barley is also grown in regions with greater rainfall and more fertile soils, mainly as a rotation crop with vegetables.

Most of Tasmania's barley is used for stock feed, which is imported from the mainland. Local production of feed grade barley cannot compete with mainland prices and therefore growers aim to supply the malting market. If a crop does not meet malting standards it is then downgraded to fodder grain. Malting barley receives a premium price compared with other cereals and is used for beer and whisky production. This gives producers the

incentive for growers to aim to produce barley with a plump, even grain that have a protein content between 10.5 and 11.5% (Eagles *et al.* 1995).

Tasmania's high rainfall, mild climate and access to irrigation permit a longer growing season than much of the mainland wheat belt allowing greater yield potential. Similarities between Tasmanian and United Kingdom climates has raised questions as to why Tasmanian cereals yields do not reflect those in the UK, which average between 4 and 5 t/ha and commonly reach 10 t/ha (Russell and Mendham 1985a). Experiments carried out by Russell and Mendham (1985b) and Mendham and Russell (1986) demonstrated that barley could achieve yields of up to 10 t/ha. However, crops yields are often restricted by waterlogging, frost at flowering and biotic stress.

Barley has traditionally not been an irrigated crop even though water stress is a common yield constraint (Russell and Mendham 1985b). Competition for available water from high value crops such as poppies and processing vegetables limits the irrigation of barley and other cereal crops grown in Tasmania. On soils with high productivity barley is often used typically as a break crop in rotation with cash crops. However, the development of locally adapted barley varieties with stronger stems and greater resistance to diseases is making irrigation a cost effective method of producing high yields for stock feed and malting (O'Keefe and Fettell 2010).

Water-use efficiency (WUE) and its importance in agricultural production has been well documented and have been the focus of many detailed studies (Sadras and Angus 2006b; French and Schultz 1984a). The early stages of WUE research simply considered the relationship between rainfall and yield (Richardson 1923). This was later expanded

through an extensive study by French and Schultz (1984a), which also accounted for soil evaporation, to develop a simple method of calculation WUE. This model has been widely used in southern mainland Australia as a simple and effective method for simulating potential yield in response to available rainfall (Robertson and Kirkengard 2005). Since then, many other studies such as Perry (1987a) and Sadras and Angus (2006b) have further developed the WUE model to account for further losses within the system such as runoff and deep drainage, which are of particular importance in higher rainfall zones (Botwright Acuña *et al.* 2015). Perry (1987a) detailed the water balance equation of soil moisture, rainfall, surface evaporation, transpiration, runoff and deep draining however, quantifying the occurrence of amount of water loss has proved difficult as it is hard to measure deep drainage and run off.

Many farming regions within Tasmanian contain soils with complex physical characteristics such as Kurosols, and Chromosols that pose issues in regards to cropping (Cotching *et al.* 2009). Texture contrast soils occupy a majority of southern Australian agricultural regions and can be difficult to crop and manage due to its physical characteristics (Gardner *et al.* 1992; Anderson *et al.* 1992; Turner 1992; Edwards 1992). The abrupt change in texture between the topsoil and clay subsoil means there is a large contrast in the permeability of the two soil horizons (Tennant *et al.* 1992). Texture change in the soil profile increases the incidence of waterlogging, which reduces plant growth and leads to a weaker and shallower root system, with restricted development deeper into the clay subsoil (Edwards 1992; Gardner *et al.* 1992).

Mendham and Russell (1986) documented issues with waterlogging in barley experiments grown on texture contrast soils in Southern Tasmania, particularly with later sown crops.

This is due to wet winters and erratic spring rainfall patterns, which have a greater impact on crop that have not properly established a root system. Projections for Tasmania's rainfall indicate that a majority of the year will be drier with an increase in winter rainfall (Pook 2001) exacerbating the impact this weather pattern has on crop sowing periods and establishment. Despite moisture stress and waterlogging limiting barley yields, and forecasts that these issues will become more prevalent, there have been limited field studies evaluating the barley growth on texture contrast soils in these conditions

This chapter examines the effect that soil moisture has on barley growth and yield with the use of irrigation to evaluate how water-use efficiency can be influenced on barley grown on texture contrast soils.

## **2.2 Materials and methods**

### *2.2.1 Experimental sites*

Two field experiments were conducted in 2009/10 at the University Farm, Cambridge (42°50'S, 147°31'E) and in 2010/11 at Seaton, Dulcote (42°77'S, 147°42'E) Tasmania. The soil type in the 2009/10 site was a texture contrast with sandy loam top soil and below 19 cm a subsoil dominated by clay with high smectite content (Holz 1994). The 2010/11 site was also on a texture contrast soil with sandy loam top soil to a depth of 20 cm but had a 5 cm bleached A2 horizon separating the topsoil and clay subsoil.

The 2010/11 site was mapped with an EM38 at 5 m intervals to measure electric conductivity as affected by soil water, texture and salinity to locate plots within areas of uniform soil conditions (Figure 2-1). EM38 is an electromagnetic induction sensor that measures the apparent electrical conductivity in soils that can pick up variations in soil properties.

At both sites, barley, cv. Gairdner, dressed with Bytan was sown on 5 October 2009 and 26 August 2010. Seed was sown at 100 kg/ha using a John Shearer double shoot drill seeder at a target depth of 40-50 mm with a row spacing of 150 mm. Fertiliser in the form of Campbell's Rustica (12:5:14:8) at 128 kg/ha was drilled below seed depth at sowing. The 2009/10 experiment had been topdressed with 80 kg/ha urea on 25 November, while the 2010/11 experiment received 100 kg/ha on 27 October and 80 kg/ha on 5 November. Plots in both experiments were 20 m long x 10.5 m wide with five replicates.



### 2.2.2 *Soil moisture monitoring*

Soil moisture in the 2009/10 experiment was monitored using soil tension sensors, MEA G-bugs. These were installed in each plot in replicates 1 and 3 on 19 November. Two GBLite sensors measuring soil tension range of 0 – 200 kPa were installed at depths of 30 and 70 cm respectively. Data was logged with a MEA retriever and analysed using MEA Bug Software Version 6.01.06.

Soil in the 2010/11 experiment was monitored using Sentek EnviroSCAN probes. The EnviroSCAN probes replaced the G-bugs sensors from the previous year in order to more accurately monitor soil moisture using an undisturbed installation method without the use of a slurry infill surrounding the sensors. Three PVC access tubes were installed in each plot prior to sowing (Figure 2-1). Two EnviroSCAN probes had eight sensors at depths of 10, 20, 30, 40, 50, 70, 90 and 110 cm. Probes were placed in each plot in intervals to log soil moisture and water movement during rainfall and irrigation events. Data was logged at 10 minute intervals and reduced to 1 minute during irrigation and retrieved using Sentek PC configuration software.

Prior to sowing, soil samples were taken in both sites to measure a range of soil characteristics to parameterise APSIM. Soil analyses, which included texture, pH (CaCl<sub>2</sub> and H<sub>2</sub>O), ammonium nitrate, nitrate nitrogen, phosphorus colwell, potassium colwell, sulphur, organic carbon, and conductivity were carried out at CSBP Laboratories, Western Australia.

Table 2-1. Irrigation and rainfall amounts (mm) from the 2009/10 and 2010/11 field experiments.

	Irrigation	Rainfall	Total
2009/10 (Aug – Jan)			
Low	17	162	179
Medium	34	162	196
High	59	162	221
2010/11 (Oct – Jan)			
Rainfed	0	252	252
Optimum	37	252	289
Waterlogged	116	252	368

### 2.2.3 *Experimental design*

The 2009/10 experiment had three treatments, however a wet season led to limited irrigation with low (17 mm), medium (34 mm) and high (59 mm) irrigation with five replications (Figure 2-1). Irrigation timing in the 2009/10 experiment was determined by the farm manager by examining moisture the topsoil and climatic forecasts.

The 2010/11 experiment consisted of three treatments rainfed, optimum and waterlogged with five replications. The rainfed treatment received no irrigation. A combination of soil pits and EnviroSCAN moisture readings were used to schedule irrigation the optimum treatment, whereas to simulate waterlogging on top of the clay subsoil, five large irrigation events (ranging from 24 and 36 mm) were applied to the waterlogged treatment (Table 2-1). Plots were irrigated using six Nelson sprinklers with a spray diameter of 20 m, paired and placed in both ends and middle of the plots. Sprinklers were regulated at 50 psi and a total average application of 8 mm/hour.

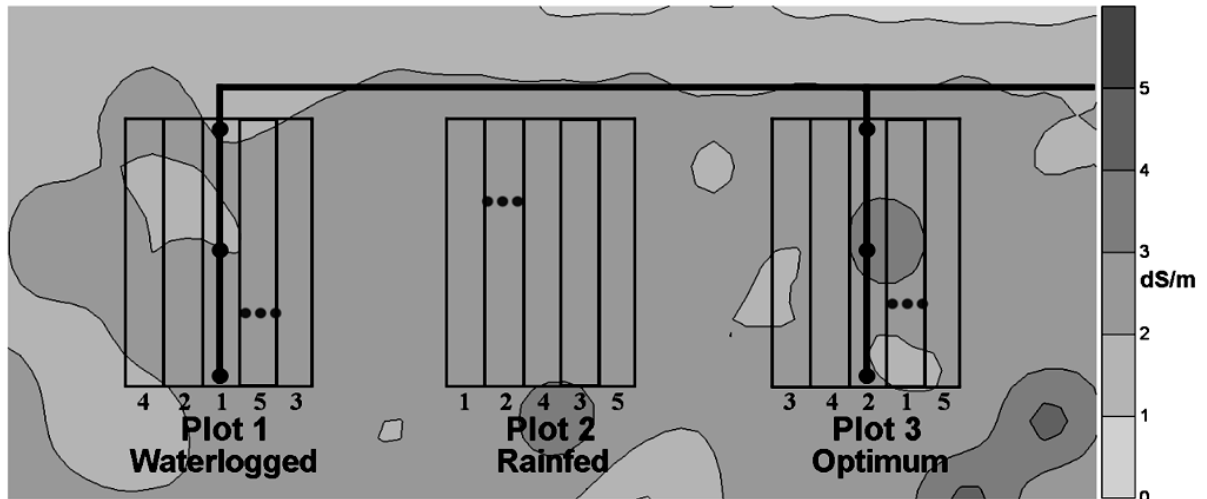


Figure 2-1. Experimental design overlapping EM38 mapping of the field site. Large dots represent pairs of sprinklers and the small dots represent the position of the EnviroSCAN tubes.

#### 2.2.4 Plant sampling

Plant establishment in the 2009/10 experiment was measured 13 days after sowing (DAS). Four counts of established plants in one lineal meter were taken on rows four and eight in each replicate. This data was then used to determine the number of plants/m<sup>2</sup>.

Plant establishment in the 2010/11 experiment was measured 21 days after sowing (DAS). Three counts were taken in each replicate using a 1 m<sup>2</sup> quadrat to determine plants/m<sup>2</sup>.

Plant samples for both experiments were conducted at elongation (GS 31), ear emergence (GS 55) and maturity (GS 89) (Zadoks *et al.* 1974). Five plants were randomly selected from the 1 m<sup>2</sup> quadrat sample and measured for height, growth stage, and tiller number. The sub-samples were then separated into leaves, stems and dead leaves and at maturity, ears. Leaf area was determined using an Epson Expression 10,000 XL image scanner with the computer program WinFOLIA 2006a and the leaf area index (LAI) calculated.

At maturity, ears from both experiments were weighed, counted and threshed. The grains were then counted and weighed to calculate grains/ear and individual grain weight. Grain subsamples were taken from the bulk yield to assess grain nitrogen for the 2010/11 experiment. A sample of 20 g of grain was ground and analysed for crude protein content by Cumberland Valley Analytical Services, Hagerstown MD.

Following harvesting of the 2009/10 experiment, 10 x 45mm diameter soil cores were extracted using a hydraulic auger to a depth of 1 m from each plot. The cores were cut into 10 cm sections in the lab and root number was determined using the core-break method (van Noordwijk *et al.* 2000). Results of the root analysis are presented in Chapter 3.

#### 2.2.5 *Statistical analysis*

Analysis of crop data was carried out using SAS Statistics 9.2 with linear mixed models used to test the significant effects of irrigation treatments. The least significant difference LSD of significant data was reported for  $P < 0.05$ .

#### 2.2.6 *WUE calculations*

The ASPIM WUE calculation was derived by dividing total water-use by yield from simulations that were the major focus of Chapter 4. Water-use was defined as the accumulation of simulated water use by the crop and possible forms of water loss throughout the cropping system (Botwright Acuña *et al.* 2015).

## 2.3 Results

### 2.3.1 *Crop growth of barley at maturity in 2009/10*

Measurements taken during vegetative growth (64 DAS) and anthesis (88 DAS), gave no significant differences in crop growth or development between treatments (data not shown). At maturity, plant height was greatest in the medium irrigation treatment, 1.9 and 15% taller than the high and low irrigation treatment, respectively (Table 2-2). Dry matter followed a similar trend with a significant difference found only between the low and medium irrigation treatments. Likewise, yield was greatest in the medium irrigation treatment, 9.3% greater than the high irrigation treatment and 24.3% than the low irrigation treatment.

Table 2-2. Effect of irrigation on plant growth and yield at maturity in the 2009/10 season.

Treatment	Plant Height (cm)	Dry Matter (t/ha)	Yield (t/ha)
Low	54.6	13.1	3.56
Medium	64.2	15.6	4.61
High	63.0	14.0	4.18
Lsd ( $P>0.05$ )	3.3	2.4	0.53

### 2.3.2 *Vegetative development of barley in 2010/11*

At anthesis (88 DAS), plant height was 12% shorter ( $P>0.05$ ) in the rainfed treatment compared with the remaining treatments, which had similar heights of approximately 81 cm. Tiller number per plant was greatest in the waterlogged treatment with 1.3 tillers more than either the rainfed and waterlogged treatments. Stem weight decreased with irrigation and was significantly reduced ( $P>0.05$ ) in the waterlogged treatment compared with the

rainfed and optimum treatments. LAI was greatest in the optimum treatment and reduced by 16% in the waterlogged treatment. LAI decreased by a further one third in the rainfed treatment. Total dry matter followed the same trend as LAI, however the only significant difference existed between the optimum and rainfed treatments (Table 2-3).

Table 2-3. Effect of irrigation on plant growth and development at anthesis in the 2010/11 experiment (88 DAS).

Treatment	Plant Height (cm)	Tiller No/Plant	Stem Wt/Plant (g)	LAI	Dry Matter (t/ha)
Rainfed	71.1	5.4	3.23	2.93	7.2
Optimum	81.2	5.4	3.41	5.09	9.5
Waterlogged	81.5	6.7	2.95	4.29	8.5
Lsd (P>0.05)	4.5	0.62	0.19	0.71	1.31

### 2.3.3 *Yield and yield components of barley at maturity in 2010/2011*

Total dry matter followed the same trend seen at anthesis. The optimum treatment had the greatest dry matter approximately 16% greater than the other treatments. At maturity, plant height significantly decreased with irrigation across treatments (Table 2-4). Although the waterlogged treatment had more tillers at 88 DAS, by maturity the optimum treatment had the greatest number of fertile tillers with 2.4 and 9.2% more fertile tillers than the waterlogged and rainfed treatments, respectively. Ear weight was greatest in the rainfed treatment and decreased with irrigation. The optimum and rainfed treatments had the greatest grain weight, both 25% heavier than the waterlogged treatment. Yield in the optimum treatment was significantly greater than the waterlogged and rainfed treatments, 0.9 and 1.5 t/ha respectively. Grain in waterlogged treatment contained the least percentage of protein at 12.8%. Less irrigation increased grain protein.

Lodging was an issue in the waterlogged treatment with an average of 57.5% of the plots lodging at the stem (Table 2-4). The rainfed showed no signs of lodging while the optimum treatment only exhibited a minor amount of lodging (7.9%).

Table 2-4. Effect of irrigation on crop growth, yield, yield components and lodging at maturity.

Treatment	Plant Height (cm)	Fertile Tillers (%)	Grains/ear	Grain Weight (mg)	Grain protein (%)	Dry Matter (t/ha)	Yield (t/ha)	Lodging (%)
Rainfed	59.6	78.1	18.4	0.051	13.8	12.9	4.87	0.0
Optimum	79.1	87.3	23.5	0.050	13.2	15.6	6.38	7.9
Waterlogged	88.3	84.9	20.3	0.038	12.8	13.2	5.49	57.5
Lsd (P>0.05)	3.87	6.43	1.44	0.005	0.81	1.75	0.53	12.5

#### 2.3.4 Simulated water use and water-use efficiency using APSIM

APSIM predicted that there was no water loss through pond evaporation or lateral flow within the subsoil (Table 2-5). There was no drainage of water past the root zone in the rainfed and optimum treatments, whereas there was a total of 56 mm of water lost through deep draining in the waterlogged treatment. APSIM outputs recorded minimal runoff occurred with a total of 1 mm in all treatment simulations. Simulated soil evaporation was greatest in the waterlogged treatment with 139 mm lost, 8 and 5 mm water lost through evaporation than the rainfed and optimum treatment respectively.

Plant water uptake was the greatest form of water loss from the soil profile across all three treatments. APSIM simulated 143 mm of plant water uptake in the rainfed treatment, the least of the three treatment simulations compared with a 29% increase in the optimum and waterlogged treatments.

Table 2-5. WUE calculation of irrigation treatments using plant water-use and water loss data derived from APSIM simulations. All forms of water loss from the soil profile were measured in mm.

	Rainfed	Optimum	Waterlogged
Water components			
Pond evaporation	0	0	0
Lateral flow	0	0	0
Drainage	0	0	56
Runoff	1	1	1
Soil evaporation	131	135	139
Plant water uptake	143	200	198
Total water use (mm)	275	336	394
Yield			
Observed grain yield (kg/ha)	4860	6380	5480
APSIM yield (kg/ha)	4935	6437	6350
Water-use efficiency (kg/ha.mm)	17.7	19.0	13.9



## 2.4 Discussion

### 2.4.1 2009/10 field experiment

The 2009/10 field did not demonstrate many major treatments effects due to high initial soil moisture and excessive rainfall during the short growing season that nullified irrigation treatment effects. However, greater yield and biomass in the medium irrigation treatment suggested that crop growth was affected by periods of water stress and waterlogging, common characteristics found in vertic, texture contrast soils (Russell and Mendham 1985b; Edwards 1992). This led to the following year's field experiment, which was desired to have better control of irrigation scheduling and continuous soils moisture monitoring in order to capture the soil, moisture and plant interactions on yield.

Soil cores taken at the end of the 2009/10 season gave an interesting insight in this preliminary experiment into the root growth of barley in these texture contrast soils. The general consensus of growers in the region regarding root growth is that annual crops, including barley, only inhabit and utilise the upper 30 – 40 cm of the soil (Gunn *et al.* 2010, pers. comm.). However, data demonstrated that root growth can reach depths of 90 cm (detailed data presented in Chapter 3). This raised the question; can strategic irrigation in these hydrological complex soils improve yield and yield components while improving overall WUE?

### 2.4.2 Yield and yield components

The 2010/11 field experiment results confirmed the trend seen in yield and biomass in the 2009/10 trials. Furthermore, variation in yield components affected grain yield and grain

quality. The reduction in yield in the waterlogged treatment compared with the optimum was primarily due to a reduction in grain weight. The crop had the greatest percentage of tillers but many of these tillers were infertile, presumably due to waterlogging. This physiological process was explained by Gallagher *et al.* (1976) in that grain number is set before anthesis and determined by environmental conditions to ensure adequate grain fill. If conditions are more favourable for crop growth before anthesis than during grain fill, the number of seeds set may be too great and therefore not adequately filled.

Grain size is one of the most important factors for producing high quality malting barley. Larger grain contain more starch, which produces a higher percentage of extract during the malting process (Mendham 1994). Malt extract is inversely related to protein levels (Eagles *et al.* 1995) therefore it is important to ensure a plump grain while minimising grain protein for high quality malting barley. In commercial production, small grain would result in a loss of premium prices that growers can receive through the sale of the harvest to brewers. Although the yield of the waterlogged treatment was greater than the rainfed treatment, the poor grain size reduced the quality from malting to feed grain. This highlights the importance of avoiding waterlogging stress in texture contrast soils possibly by decreasing irrigation amounts but increasing their frequency.

Increased yield within the optimum treatment was due to an even contribution from all yield components; fertile tillers, grain number and grain weight. This indicates the crop had sufficient access to moisture throughout the season. Barley grown at reduced moisture stress has been shown to accumulate greater levels of starch in the grain (Gyles *et al.* 1987) therefore promoting favourable malting properties. Grain protein is required to be between 10.5 and 11.5% to be considered malting quality (Eagles *et al.* 1995). Grain protein was

greater than the acceptable level in all treatments, which would lead to cloudiness in beer production (Mendham 1994). This was most likely due to the high amounts of residual soil nitrogen and urea applied to minimise the potential for N deficiency across the treatments.

The rainfed treatment had the poorest yield of the three treatments. This was caused by low ratio of fertile tillers and reduced grains/ear (Table 2-4). These results are consistent with studies carried out by Aspinall *et al.* (1964) and Giunta *et al.* (1993), who evaluated barley growth under periods of moisture stress. However, the rainfed had the greatest ear weight of the three treatments, which contrasts with the results reported by Aspinall *et al.* (1964), Giunta *et al.* (1993) and Jamieson *et al.* (1995). Water stress prior to anthesis may have reduced the number of fertile tillers and grains/ear, but more favourable conditions during grain fill allowed grain size to reach its potential.

#### 2.4.3 Lodging

Lodging can occur in the stem or the base of the plant and depends on three factors; the forces applied to the plant, the strength of the stem and the anchorage strength of the nodal roots (Crook and Ennos 1994). The waterlogged treatment experienced lodging during grain filling as a result of a 19 mm rainfall 94 DAS. The bend point in this instance occurred in the root system of the plant. The excessive force applied to the stem was likely to be a combination of plant height, ear weight and the additional weight from the water droplets. However, the most important factor was the anchorage strength of the nodal roots (refer to Chapter 3), potentially due to a reduction in root number in the upper 5 cm of soil of the waterlogged treatment. This, together with the increased soil moisture and friable topsoil may have decreased how well the plants were anchored to the ground.

Lodging may have played a part in reducing grain weight, but literature is divided over the effect that lodging during grain fill has on final yield and yield components of cereals. Caierão (2006) reported that lodging after ear emergence had minimal effect on yield and in particular grain weight and reasoned that it was because carbohydrate assimilation that later fuels grain fill has already occurred. However Day and Dickson (1958) and Sisler and Olson (1951) concluded that lodging did reduce translocation of carbohydrates to the grain, which had a significant reduction on yield and malting quality of barley including decreasing grain size. Caierão (2006), Day and Dickson (1958) and Sisler and Olson (1951) all reported that lodging during grain fill reduced malting quality, largely due to the increase in protein to carbohydrate ratio. Lodging also decreases grain yield by reducing harvest efficiency as the crop rests close to the soil surface and beyond the reach of the combine. Severe lodging in humid, lodged conditions at high plant densities can lead to fungal growth on the ears and when harvesting is delayed, post maturity sprouting can occur, spoiling the crop (Berry *et al.* 2004). The optimum treatment experienced minor lodging (Table 2-4) at 110 DAS during an irrigation event, however it was not severe enough to effect grain quality or ease of harvesting.

#### 2.4.4 *Water-use efficiency*

Calculation of WUE can involve a variety of methods, such as French and Schultz (1984b) who developed the WUE term kg/ha.mm. This is a simplistic method that is calculated by dividing yield by the water-use of the crop, which is derived through growing season rainfall/irrigation in excess of soil evaporation. There are several drawbacks to the (F&S) approach, particularly in relation to its potential use in Tasmania. It does not take into

consideration the distribution of rainfall or the amount of water the crop has used (Perry 1987b). It also assumes that runoff and deep drainage are negligible (Robertson and Kirkengaard 2005).

Tasmania, being mostly in the HRZ, has quite variable WUE due to yield limitations such as waterlogging or water lost by via drainage, which also leaches water soluble nutrients such as nitrogen (Botwright Acuña *et al.* 2011). Using APSIM, Botwright Acuña *et al.* (2010) reported WUE of barley ranging between 7.7 to 24.3 kg/ha.mm. and in another study 3.69 to 18.03 kg/ha.mm (Botwright Acuña *et al.* 2015). Results in this experiment varied from 13.9 to 17.7 kg/ha.mm., falling in the same range as demonstrated by these data sets. The waterlogged treatment had the lowest WUE. This was not due to increased plant water use but loss of water through deep drainage with runoff being negligible across treatments. The high WUE in the optimum treatment was potentially due to an efficient use of minimal irrigation, but more importantly the increase in root depth and greater access to stored soil moisture. This is potential a valuable form of crop available water, as soils are recharged from slight winter dominant rainfall. Botwright Acuña *et al.* (2015) reported in the data set a high variance between the attained WUE and the potential WUE as predicted by APSIM. Attainable WUE is limited by crop management whereas potential WUE is determined by climate with no management and biological constraints (Botwright Acuña *et al.* 2015). This highlights the some of the inefficiencies APSIM contains in accounting for yield limiting factors such as waterlogging and root growth restrictions in heavy clay soils. However, the model allows for estimations of WUE by considering factors that difficult to quantify and will improve with constant adaptations of crop and soil parameters.

## 2.5 Conclusion

This chapter demonstrated that strategic irrigation to soil conditions could be used to increase yield and WUE in barley on texture contrast soils. It was highlighted that only four irrigations on 9 mm could increase yield by up to 23%. However observations suggest that it was not solely the amount of irrigation that led to improved yield but also the timing of application. The waterlogged treatment demonstrated that a crop may appear to have improved leaf area, height and the appearance of a very healthy crop. However, waterlogging can cause unforeseen issues such as unbalanced ear to grain number ratio or poor stem development, which can lead to poor grain quality or lodging at maturity. This is of greater importance as barley is increasingly sought for malting quality.

The difficulties of cropping texture contrast soils have been well documented (Gardner *et al.* 1992). However, although strategic irrigation led to an increase in yield through improved root growth, the relationship with the soil physical characteristics are not fully understood. This includes interactions of soil moisture with soil strength and shrinkage cracks and how this affects root depth and architecture. This will be further discussed in Chapter 3. Understanding these interactions can give further insight into irrigation management on vertic texture contrast soils to improve yield and WUE.

### **3.0 Chapter 3 – Root and soil interactions of barley on a texture contrast soil**

#### **3.1 Introduction**

Texture contrast soils occupy approximately 20% of Australia and roughly 80% of Southern Australian agricultural regions (Stevens *et al.* 1999). Despite the widespread occurrence of these soils, little is known about how their chemical and physical properties influence plant root growth and architecture. The key characteristics of texture contrast soils is the abrupt change in soil texture between the sand to sandy loam A horizon and the clay subsoil. This change in soil texture is often accompanied with abrupt changes in infiltration rate, penetration resistance and soil chemistry (Tennant *et al.* 1992).

The difficulties of cropping texture contrast soils has been well documented (Gardner *et al.* 1992; Anderson *et al.* 1992; Turner 1992; Edwards 1992). With respect to root growth, the clay subsoils promote development of perched water tables and waterlogging (Tennant *et al.* 1992), while root penetration through the clay subsoil is often restricted to shrinkage cracks and decayed roots (White and Kirkegaard 2010). Pankhurst *et al.* (2002) showed that up to 80% of roots within texture contrast soils were contained within these cracks, which reduced available water and lead to an earlier onset of moisture stress. Opportunity for root elongation through the subsoil therefore depends on the vertic nature of the soil and soil moisture status. The mechanism by which root elongation is influenced by soil moisture, shrinkage cracks and penetration resistance is poorly understood.

The low water holding capacity of the A horizon and the low permeability of the B horizon, makes texture contrast soils prone to waterlogging, particularly under irrigation (Tennant

*et al.* 1992). Waterlogging is exacerbated in many cropping areas by a winter dominant rainfall pattern and therefore crops can be under waterlogging and moisture stress within a number of weeks (Turner 1992). Waterlogged soils during crop establishment reduces plant growth and lead to weaker, shallower root systems, restricting their development deeper into the clay subsoil (Edwards 1992; Gardner *et al.* 1992). Reduced rooting in the subsoil may lead to stored soil moisture remaining unavailable to the crop towards the end of the growing season.

Within the southern cropping regions of Tasmania, many growers perceive that root development in texture contrast soil is confined to the upper 30-50 cm, due to high penetration resistance of the clay subsoil (Gunn *et al.* 2010, pers. comm.). However, when appropriately managed, texture contrast soils are no less productive than many other soils in the same region (Anderson *et al.* 1992).

This chapter investigates the relationship between root growth and irrigation scheduling on the depth and distribution of barley roots in a texture contrast soil with a shrink-swell subsoil. This chapter investigates specifically how irrigation strategy can influence root depth and distribution, soil cracking patterns and penetration resistance. It also examines whether root growth is best promoted in dry cracked subsoils or moist low penetration resistance subsoils.



## **3.2 Materials and methods**

### *3.2.1 Experimental design*

For experimental site and design, refer to materials and methods for 2010/11 experiment in Chapter 2.

### *3.2.2 Root and soil sampling*

Following harvesting of the 2010/11 season, 1m<sup>2</sup> pits were manually excavated surrounding the 3 EnviroSCAN access tubes. A 1m<sup>2</sup> grid with 10 x 10 cm cells was placed on the soil surface such that root number, presence of shrinkage cracks was recorded for each cell. Root counts included only vertically orientated roots. Assessments were conducted at 5, 10, 20, 30, 40, 50, 70, 90 and 110 cm depth or until root growth ceased.

Penetration resistance was determined in every second cell using a Rimik CP20 Cone Penetrometer. Soil samples were obtained from every second cell for determination of gravitational moisture content. Samples were oven dried at 105°C for 48 hours. This procedure was carried out at for all subsoil clay layers.

### *3.2.3 Soil profile analysis*

Physical properties of the soil profile shown in Figure 3-1 and describes using Isbell (2002) as follows:

A1: 0-20/22 cm; Colour (10YR 2/2 moist, dry); loamy sand; weak subangular blocky structure; loose consistency (dry); few pores; many fine – medium barley roots; sharp wavy boundary.

A2: 20/22-25 cm; Gray (10YR 2/1 moist, 10YR 6/1 dry); clayey sand; weak subangular blocky structure; very weak consistency (dry); many charcoal black (10YR 2/1) mottles; many fine – medium barley roots; diffuse smooth boundary.

B21: 25-55 cm; Light olive brown (2.5Y 5/3); medium heavy clay; strong columnar structure; very strong consistence (dry); many fine – medium barley roots; diffuse smooth boundary.

B22: 55-85 cm; Olive brown (2.5Y 4/4); medium clay; strong angular blocky structure; strong consistency (moist); few coarse 5 – 10 mm fragments; common fine barley roots; gradual smooth boundary.

B23: 85-110 cm; Dark yellow brown (10YR 4/6); light clay; firm consistence (moist); common 5 – 10 mm strong grey (7.5YR 5/6) mottles; few fine barley roots; clear smooth boundary.

C: 110+ cm; Colour (10YR 6/1); sandy clay loam; very weak consistence (moist); many 5 – 10 cm mottles (5YR 5.8).



Figure 3-1. Soil pit from which the soil profile analysis was conducted at the time of root count of the 2010/11 field trial and described using Isbell (2002).

#### 3.2.4 *Statistical analysis*

Recursive partitioning was conducted in R version 2.15.3 using the “party” package and “ctree” function to assess the impact that soil moisture, penetration resistance and crack occurrence on root number, via development of conditional inference trees. At each step of the partition a null hypothesis of no association is tested between the outcome and the covariates. The process ends if the null hypothesis is retained. If the null hypothesis is not

retained, the covariate with the strongest association is used to divide the data (Strobl *et al.* 2009). The variables included in the recursive partitioning models were; treatment (rainfed, optimum and waterlogged), root number, soil moisture, penetration resistance and the presence or absence of cracks in the cells above the target cell or the surrounding cells on the horizontal plane.

A nomenclature system was developed to describe the influence of adjacent cells on target cells. The target cell represents the three dimensional location in the soil profile in which the respective variable is influenced by surrounding cells. The target cell was assigned the symbol SSS with each surrounding cell at the same depth labelled a combination of left (L), right (R), top (T), bottom (B) side (S) and centre (C) such that SBR represents side-bottom-right to the target cell (Figure 3-2). The cell located 10 cm directly above the target cell was assigned the symbol AAA with the same identification system in the surrounding cells described in target cell layer. For example, AA<sub>v</sub> and SS<sub>v</sub> describe the average value of the surrounding cells in the same and above layer respectively.

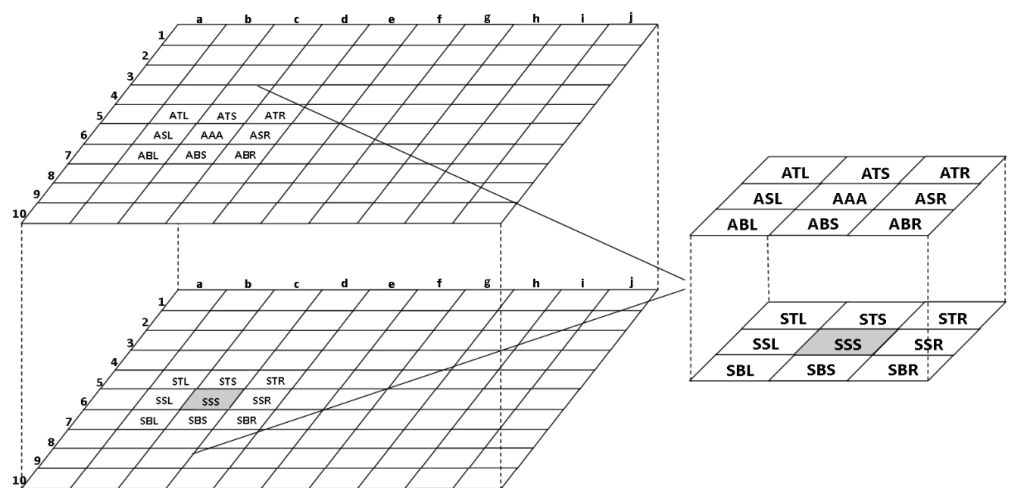


Figure 3-2. 10 x 10 cm grid nomenclature used to assess the spatial influence of soil factors, treatment effects on root number in the recursive partitioning analysis.

### 3.3 Results

#### 3.3.1 *Treatment soil water content*

Soil water content derived from EnviroSCAN probes were recorded to a depth of 110 cm for all treatments. The waterlogged treatment had the greatest median soil water content during the period of irrigation with a median of 395 mm followed by the optimum treatment of 319 mm. The rainfed treatment had a large variability of soil water compared to the other two treatments with median water content of 274 mm.

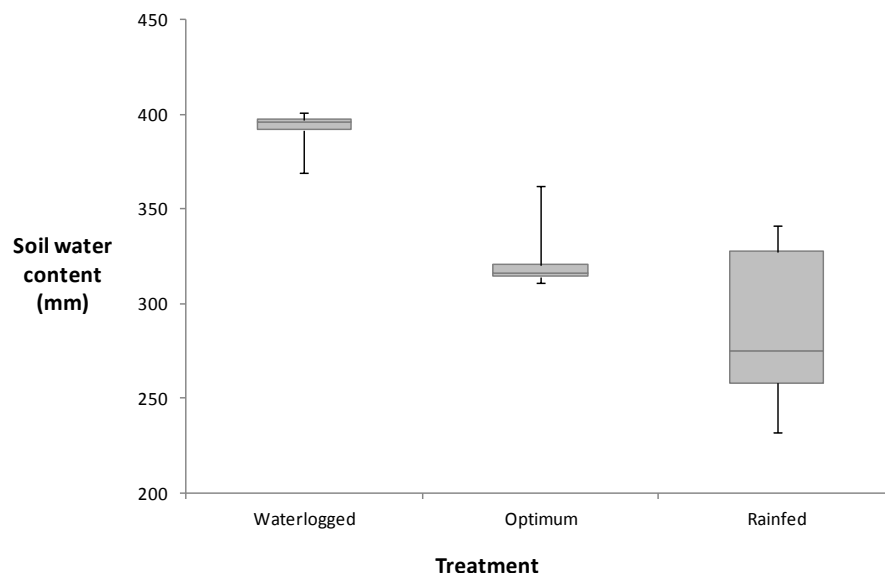


Figure 3-3. Soil moisture content taken from EnviroSCAN data of treatments to a depth of 110 cm during the irrigation period. The lower and upper edges of the box represent 25th and 75th percentiles, and the solid and dashed lines are the medians and means in each box. The 'error bars' indicates 10th and 90th percentiles

#### 3.3.2 *Root depth and distribution*

Irrigation treatment significantly influenced root depth and distribution at harvest. The rainfed treatment had a greater number of roots within the upper 10 cm compared with the waterlogged and optimum irrigation treatments. In the rainfed treatment root number

decreased with depth in a linear manner with maximum root depth at 90 cm. The optimum irrigation treatment contained approximately 35 roots/100cm<sup>2</sup> in the upper 10 cm. Maximum root number occurred at 30 cm depth with roots reaching a depth of 130 cm. The waterlogged treatment differed to that of the optimum treatment in that root number in the waterlogged treatment had a sharp decrease in root density at 30 cm. Maximum density occurred at 40 – 70 cm, then decreased to maximum root depth of 110 cm (Figure 3-4).

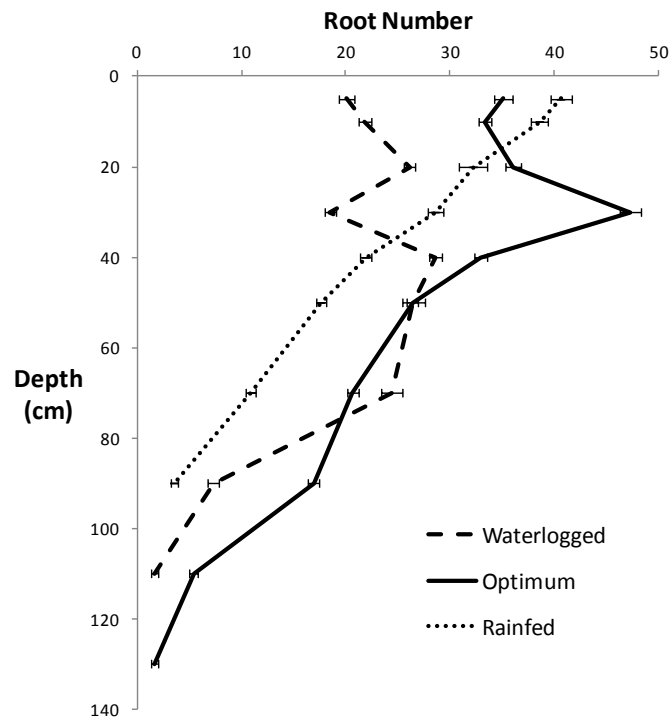


Figure 3-4. Effect of irrigation on root depth and distribution during the 2010/11 field season.

### 3.3.3 Soil moisture and penetration resistance

Penetration resistance was negatively correlated with soil moisture. The rainfed treatment had an average gravimetric soil moisture of 11.5 g g<sup>-1</sup>, in which 96% of samples had penetration resistance values greater than 2000 kPa, the threshold penetration resistance at which cereal roots are severely restricted (Hazelton and Murphy 2007). The optimum

treatment had greater average soil moisture values compared with the rainfed treatment, in which 87% of samples had penetration resistance above 2000 kPa. Average soil moisture ( $14.7 \text{ g g}^{-1}$ ) in the waterlogged treatment was greatest of the three treatments, which correlated with the lowest penetration resistance with a majority of samples (59%) falling below a threshold penetration resistance of 2000 kPa line level at which cereal root growth is severely restricted (Hazelton and Murphy 2007). The waterlogged treatment also had the greatest regression coefficient of the treatments, which decreased with soil moisture. The penetrometer could not take readings over 4000 kPa and these readings are denoted by the empty circles (Figure 3-5).

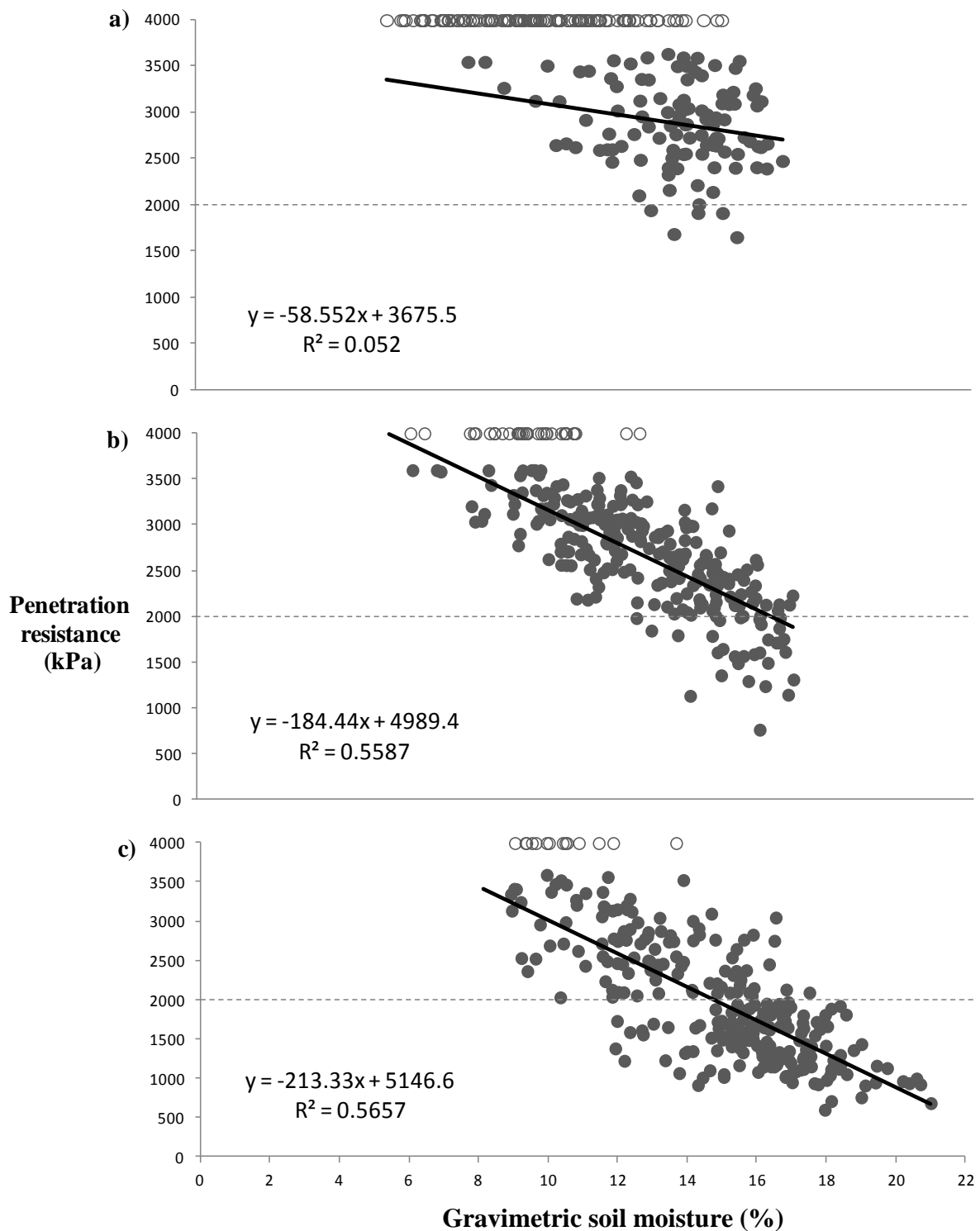


Figure 3-5. Penetration resistance of clay subsoil in relation to gravimetric soil moisture at harvest for all depths in (a) rainfed, (b) optimum and (c) waterlogged treatments. The penetrometer could not take readings over 4000 kPa (denoted by the empty circles), therefore  $R^2$  values are derived from readings under 4000 kPa only. The dotted line at 2000 kPa represents the level at which cereal roots are severely restricted (Hazelton and Murphy 2007).



### 3.3.4 Crack number with depth

Soil cracking at harvest was most common in the rainfed treatment followed by the optimum, then the waterlogged treatments (Figure 3-6a). Crack occurrence in the rainfed treatment was more prevalent in the upper 50 cm in all treatments, with between 29 and 37% of grids containing cracks. Cracking was more apparent at depth in the optimum treatment than the other two treatments having the greatest number of cracks at 70 and 90 cm. In the waterlogged treatment, cracks did not occur at either 20 cm or 90 cm depth.

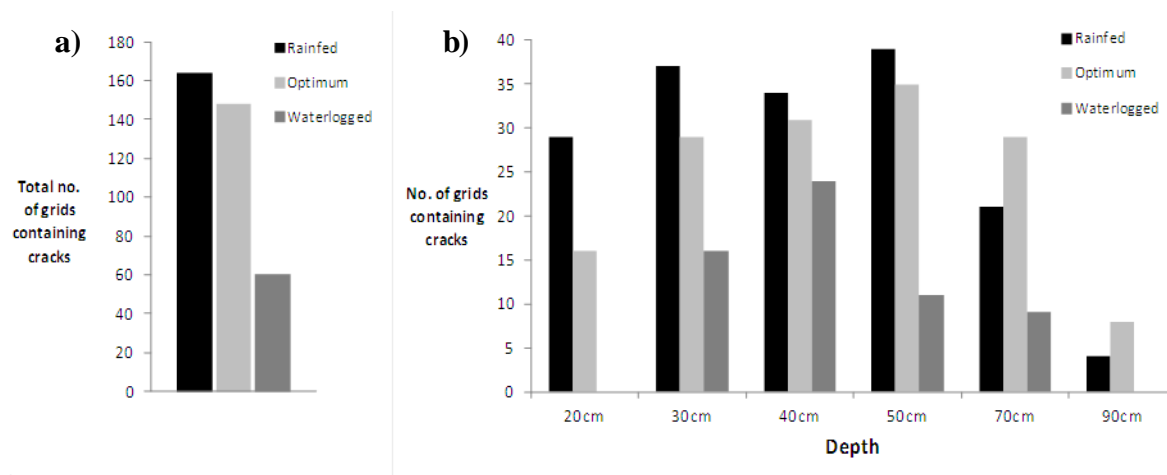


Figure 3-6. Total number of grids containing a crack in the rainfed, optimum and waterlogged treatments at harvesting (a) and the number of grids containing a crack separated into dept in each of the treatments (b).

### 3.3.5 Root and soil interactions

Principle component analysis demonstrated roots and cracks were closely related in the upper 20 cm across all treatments (Figure 3-7a). The association between roots and crack abundance decreased with depth (Figure 3-7b – d). The relationship between cracks and penetration resistance decreased with soil depth (Figure 3-7b – d). Soil strength and soil moisture remain opposed to each other regardless of death.

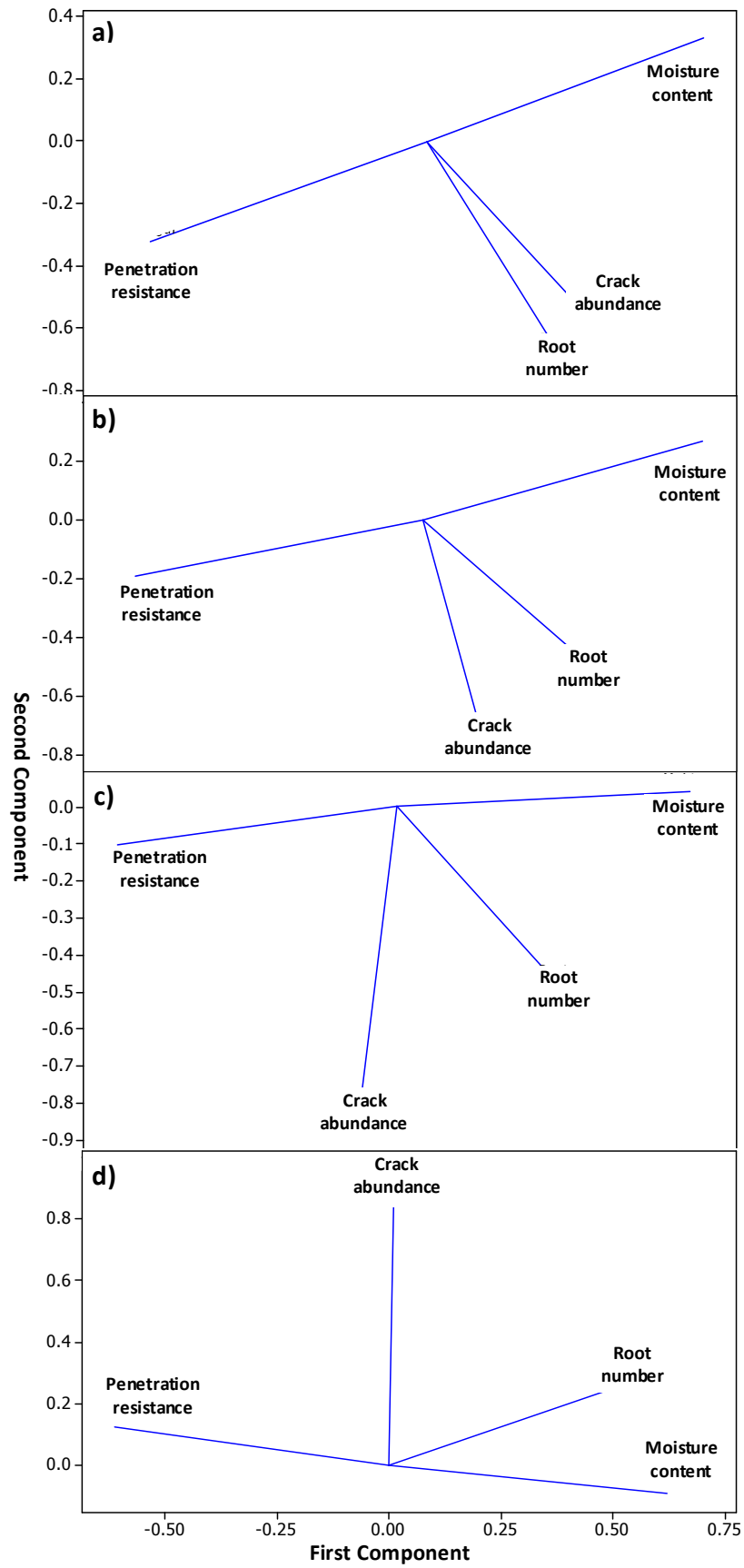


Figure 3-7. Principle component analysis of soil moisture, soil strength, crack abundance and root number for all treatments selected at (a) 20, (b) 30, (c) 50 and (d) 70 cm.

### 3.3.6 *Root and soil factor correlations*

Figure 3-8 demonstrates the degree of correlation and significance between soil moisture, strength and cracks with root number verses depth. Cracks were most significant factor influencing root number in the upper 50 cm of soil in the rainfed treatment while soil strength predominated in the lower 40 cm (Figure 3-8a). Moisture and penetration resistance displayed a very similar correlation pattern throughout the profile. Similar to the rainfed treatment, cracks were the most significant factor affecting root number in the upper profile in the optimum treatment (Figure 3-8b). Penetration resistance also had a significant influence on root number within the upper 40 cm and at 90 cm depth. The correlation pattern of soil moisture and penetration resistance on root number was diametrically opposed to each other throughout the whole profile. Cracks were also a significant factor on root number in the waterlogged treatment but unlike the rainfed and optimum treatments, this was limited to a depth of 70 cm (Figure 3-8c). Penetration resistance was also an important factor and had a highly significant negative relationship with root number at 50 – 70 cm.

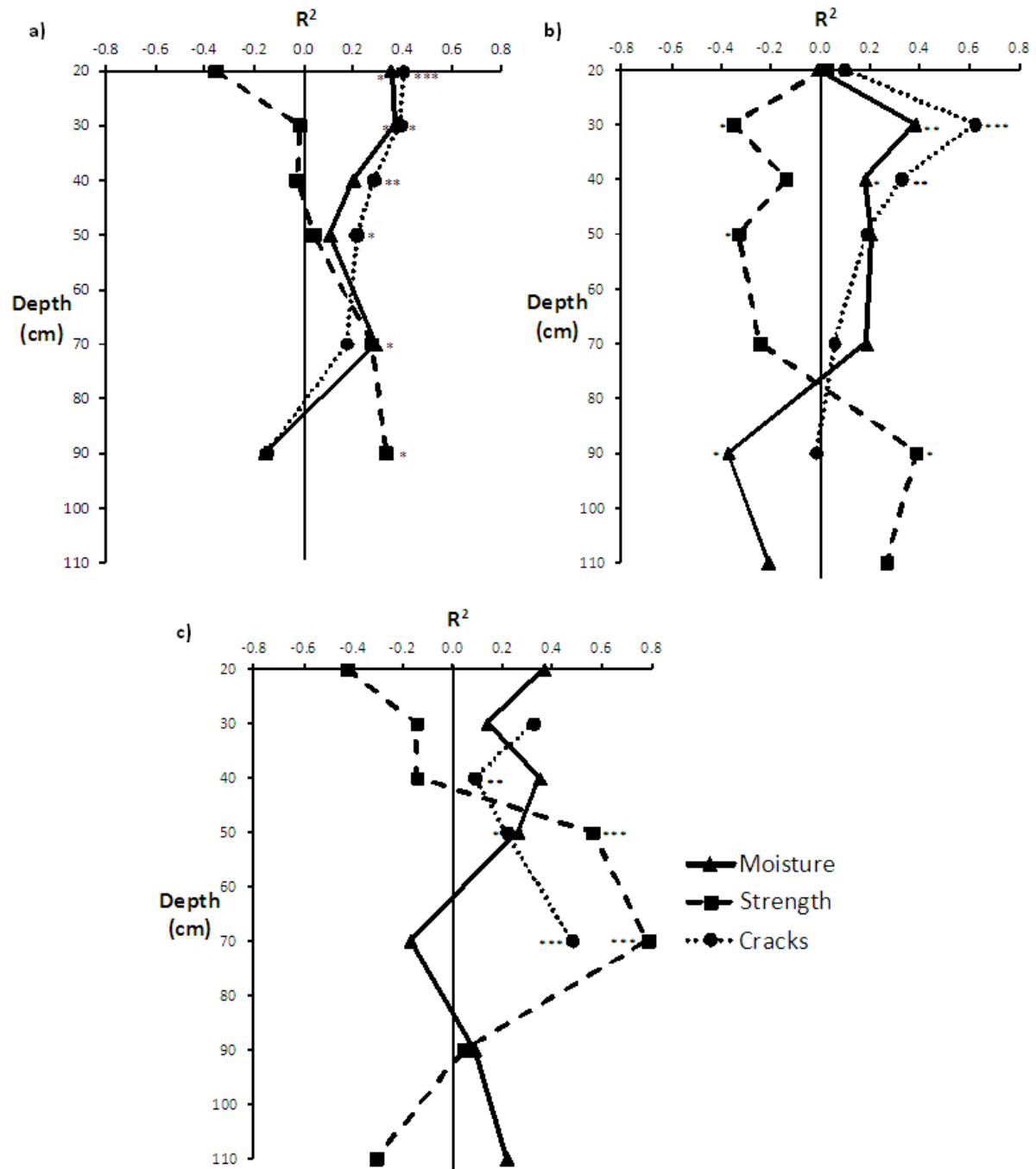


Figure 3-8. Degree and direction of correlation between soil moisture, strength and cracks with root number in the (a) rainfed, (b) optimum and (c) waterlogged treatments verses depth. \* denotes a significance of  $p < 0.05$  between root number and the soil factor at that depth, \*\*  $p < 0.01$  and \*\*\* a significance of  $p < 0.001$ .

### 3.3.7 *Recursive partitioning*

Recursive partitioning is often used as a statistical method in the classification of populations. In this study it has been used to explore the three dimensional influences of adjacent cells on a target cell. The diagram shows a conditional inference tree (Figure 3-9a), which consists of nodes and descriptive statistics within the nodes.

Node 1 is the largest predicting factor, which in Figure 3-9a is average root number in the cells above the target cell as shown in Figure 2.3. This is abbreviated as RooAAv in node 1 ( $P < 0.001$ ). The output of the recursive partitioning showed that the threshold value for RooAAv was 29.167 roots. This is shown in the branches beneath node 1. The left branch represents a cell that contains less than 29.167 roots. In the next iteration of recursive partitioning to node 2 (to the left of Figure 3-9), when there were less than 29.167 roots, RooAAv was once again the best predicting factor. The threshold value for node 2 was 15 roots, as shown in the branches below node 2. As before, in the next iteration of recursive partitioning to node 3 is for when there was less than 15 roots. The box and whisker plot shown at node 3 provides details of the variation in number of roots in these cells. The lower and upper edges of the box represent 25th and 75th percentiles, and the solid and dashed lines are the median (4 roots) in the box. The error bars indicates 10th and 90th percentiles; while the circles are outliers. Node 4, to the right of node 3 in Figure 3-9 then shows partitioning of cells containing more than 15 roots, with the box below this node representing the variation in these cells as described for node 3, with a median of 21 roots.

Returning to node 1, cells contain greater than the threshold value of RooAAv of 29.167 roots are partitioned in the right hand branch leading to node 5. Here the best predicting factor of cells containing greater than 29.167 roots is irrigation treatment. The next

iteration of recursive partitioning to node 6 was for cells in the optimum treatment that contained greater than 29.167 roots with a median of 34 roots. As described previously, the box plot beneath node 6 describes the variation in the optimum treatment. In comparison, node 7 to the far right then shows partitioning of cells containing more than 29.167 roots in the rainfed and waterlogged treatments, with the box below this node representing the variation in these cells as described for nodes 3, 4 and 6. The median the node 7 was 30 roots.

The same approach is applied for describing the 3D relationship between factors when treatment effect (i.e. irrigation) was removed from the analysis to examine the main effect of vertic soil characteristics (i.e. soil moisture content, cracks and soil strength) as shown in Figure 3-9b.

In Figure 3-9b, recursive partitioning showed that the largest predicting factor on root number (Node 1) was still RooAAv as in Figure 3-9a. Similarly, node 3 and 4 were identical to Figure 3-9a. In contrast, the predominant predicting factor for node 5 was cracks in the target cell (Crk SSS). The next iteration of recursive partitioning to node 6 was for cells without cracks (median 30) that contained greater than 29.167 roots. In comparison, node 7 to the far right then shows partitioning of cells containing more than 29.167 roots cells with cracks (median 32), with the box below this node representing the variation in these cells as described for nodes 3, 4 and 6.

This analysis so far has shown that recursive partitioning was dominated by root number in cells above the target cell. To further investigate the influence of soil moisture content,

cracks and soil strength root number (Figure 3-10a) and then root number and treatment (Figure 3-10b) were removed from the analysis.

In Figure 3-10a, the largest predicting factor (Node 1) was irrigation treatment. Within the optimum treatment, the predominant predicting factor (Node 2) was the presence of cracks in cells surrounding the target cell (Crk.SAv). If less than 2 cells contained a crack the median root number in the target cell were 22.5 (Node 3). Target cells that were surrounded by 2 or more cracks, contained a median of 31.2 roots. To the far right of the tree in Figure 3-10a, soil moisture in the surrounding cells (Moi.SAv) was the greatest predictor of root number in the rainfed and waterlogged treatments (Node 5). If soil moisture in the surrounding cells was less or equal to 10.5% the median root number in the target cell were 11.7 (Node 6). Target cells that cells that were surrounded by soil moisture greater than 10.5% contained a median of 23.3 roots (Node 7).

Figure 3-10b had treatment removed as a factor and as a result, the largest predicting factor became the presence of cracks in cells surrounding the target cell (Crk.SAv). If there were less than 2 cracks in each of the surrounding cells, the predominant predicting factor was the presence or absence of a crack in the target cell. If the target cell did not contain a crack the median root number in the target cell were 21.1 (Node 3). To the far right of the tree in Figure 3-10b, if there were two or more cracks within each surrounding cell, soil moisture in the surrounding cells (Moi.SAv) was the greatest predictor of root number. If soil moisture in the surrounding cells was less or equal to 13.678% the median root number in the target cell were 23.1 (Node 6). Target cells that cells that were surrounded by soil moisture greater than 13.678% contained a median of 30.3 roots (Node 7).

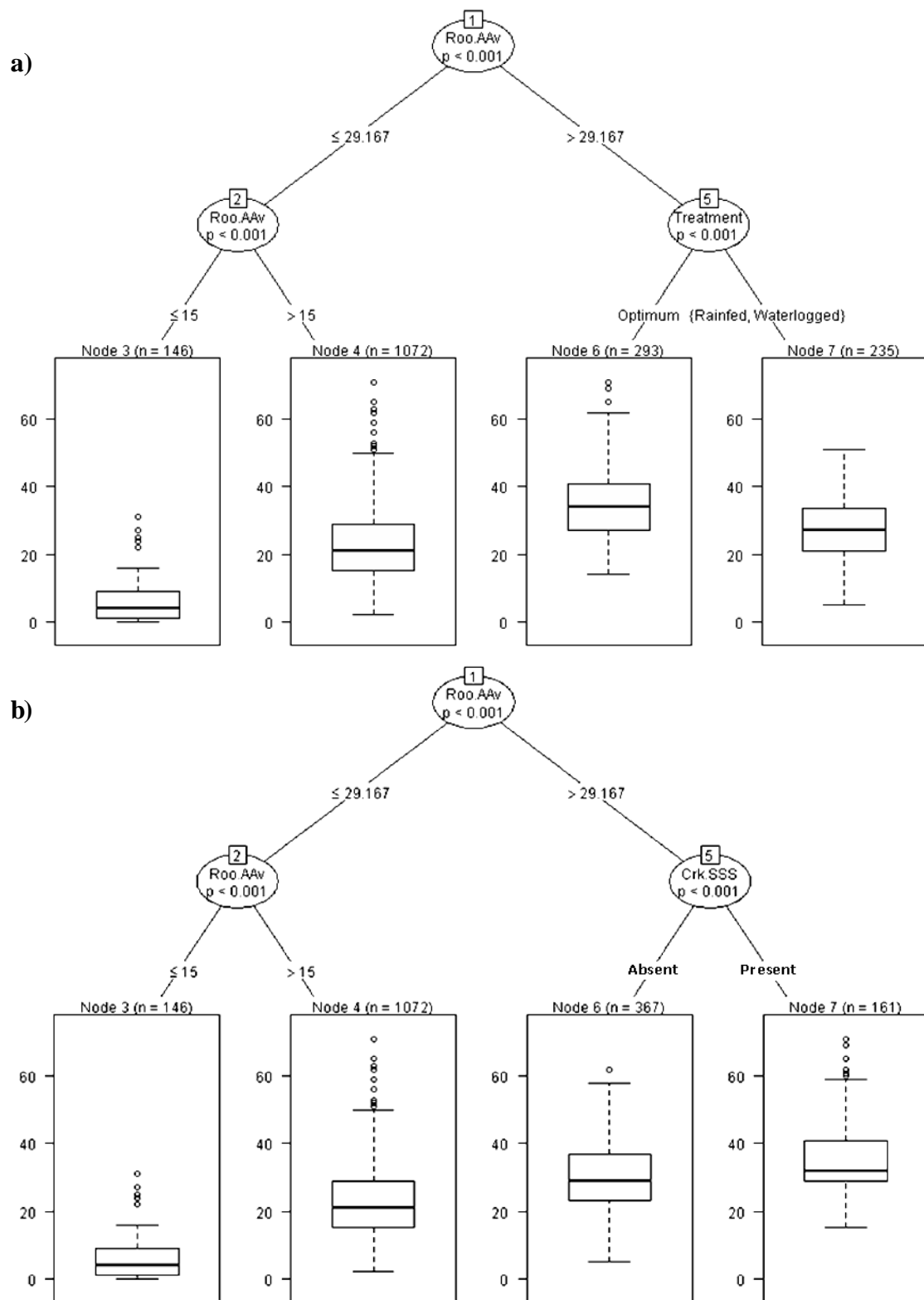


Figure 3-9. Conditional inference regression tree indicating (a) the importance of root architecture, cracking, penetration resistance and irrigation treatments on root number for any target cell and (b) after the removal of treatment as a factor.



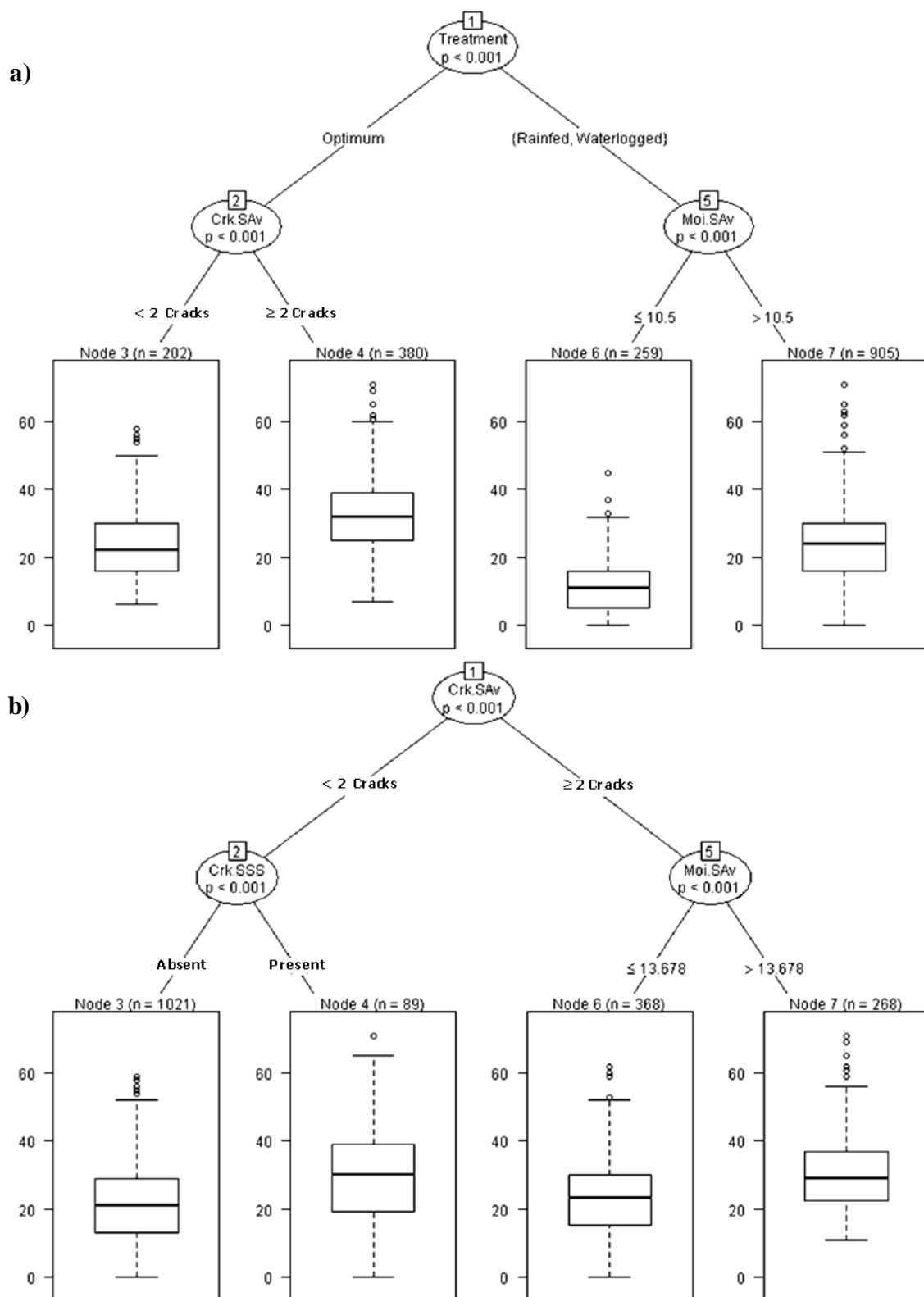


Figure 3-10. Conditional inference regression tree indicating (a) the importance of soil factors and irrigation treatments when Roo.AAv removed as a factor (b) Roo.AAv and treatment removed as a factor.

### 3.4 Discussion

#### 3.4.1 *Root growth*

Within the southern cropping regions of Tasmania, many growers believe that root growth of cereals in the texture contrast soil are confined to the upper 30-50 cm due to the high penetration resistance the clay subsoils (Gunn *et al.* 2010, pers. comm.). Results from this experiment demonstrate that barley roots reached depths to 90 cm under rainfed conditions and up to a depth of 130 cm with strategic irrigation. These rooting depths are similar to values reported by Kirkegaard and Lilley (2007) who also showed cereal roots reached depths between 80 -180 cm in texture contrast soils in the southern cropping regions. My results in part lead to subsequent, more detailed analysis in a carefully undertaken experiment that compared root growth under contrasting irrigation regimes.

The approach taken in this experiment differed from many other root count studies in that roots were counted on the horizontal plane similar to White and Kirkegaard (2010), as opposed to the vertical face of a soil or in the lab through the use of soil cores (Hoad *et al.* 2001; Kirkegaard and Lilley 2007). This allowed for greater accuracy in removing soil during the excavation process and maintaining vertical roots. It also kept shrinkage cracks intact, therefore it was possible to observe roots distribution and preferential pathways. This approach however, limited the observation of horizontal root growth into the soil matrix via crack walls. This was later accounted for by comparing crack abundance and root number in the surrounding soil matrix (Figure 3-10).

Root growth in the subsoil occurred when either (I) penetration resistance was low at high soil water content or (II) shrinkage cracks occurred at low moisture content. In the rainfed

and optimum irrigation treatments, roots were observed to be located within shrinkage cracks, which served as preferential pathways for root elongation and water movement rather than passage through the very dense soil matrix.

Root growth in shrinkage cracks have been cited in a number of studies (Strong *et al.* 2006; Watt *et al.* 2006; Whiteley and Dexter 1983), with Pankhurst *et al.* (2002) noting that up to 80% of roots can be located within cracks, which effectively reduces available water and lead to an earlier onset of moisture stress. White and Kirkegaard (2010) found that 85 - 100% of wheat roots at depths greater than 60 cm occurred within the cracks or pores of dense subsoils rather than the soil matrix. They concluded that adequate water uptake could be achieved provided there was sufficient root-soil contact. They also suggested the possibility of root elongation via cracks as a method for crops to extract greater soil moisture by gaining access to the surrounding soil matrix along crack walls. Dexter (2004) found that fully saturated clays can have a high penetration resistance. Therefore, even when saturated, the high penetration resistance of the clay subsoils still prevents exploration of the soil profile. White and Kirkegaard (2010) similarly discuss that cracks play a key role in rooting depth regardless of soil moisture.

The work reported in this chapter quantifies the relationship between roots number and soil characteristics using recursive partitioning, which have not been previously reported. It enables statistical investigation of the three dimensional influences of soil characteristics and root number on root architecture. The role that cracks have on root proliferation was highlighted by the optimum treatment where the presence of two or more cracks increased the abundance of roots in the surrounding soil matrix. However, the presence of cracks did not mean that roots then grew into the soil matrix, as shown in the rainfed treatment. The

rainfed treatment had more cracks than the optimum irrigation treatment but did not have a significantly higher root count. Even though the rainfed treatment had an abundance of cracks, this did not result in greater root exploration as the penetration resistance of the soil matrix and low moisture content combined to reduce root growth within the soil matrix. The observation of Whiteley and Dexter (1983) supports this theory, noting that lateral root growth is limited by a number of factors including moisture and root angle. Thus, the relationship cracks and root exploration is more complicated than simply just the presence or absence of cracks.

#### 3.4.2 *Irrigation*

Subsoil cracking can result in both positive and negative effects on soil water availability. Cracks have been shown to result in a loss of rainfall and irrigation via deep drainage below the crop root zone (Greve *et al.* 2010; Weaver *et al.* 2005). There is conjecture as to how to best irrigate to minimise water loss via deep drainage (Greve *et al.* 2010). Chen *et al.* (2002) proposed that application of irrigation over a longer time period was an ideal irrigation strategy. Conversely, Mitchell and van Genuchten (1993) suggested utilising the presence of the cracks by flood irrigation to maximise the high infiltration rates of these soil features. These two strategies are quite different in the amount of water required but have their merits in regards to irrigating to soil conditions. Yet it highlights that irrigation in agronomic practices is highly varied depending on water availability and irrigation application. Irrigation of cracking soils focuses on maximising water use by minimising water loss via cracks however, this raises a questions in regards to the role cracks play as macropores for root proliferation into the subsoil. White and Kirkegaard (2010) demonstrated that wheat roots were confined to soil pores at depth in dense clays, yet they

were able to access water through crack walls via root hairs. However, not all available water was accessed by the crop raising questions as to the quality of root-soil contact within these preferential pathways. Strategic irrigation to maintain favourable soil moisture within these macropores may therefore improve root-soil contact by reducing the crack diameter and decreasing the penetration resistance of soil in the crack face.

The relationship between soil moisture, soil strength and crack abundance is likely to fluctuate during and across seasons. The result indicated relationships between factors and does not imply causation. It raises the question whether roots were present due to growing down the cracks or if the cracks formed as a result of roots extracting soil moisture. This may be addressed through more detailed monitoring of soil moisture together with systematic destructive root analysis in separate soil pits within the treatment area, throughout the season.

This chapter has detailed the mechanics involved in the improved rooting depth via strategic irrigation. This raises the question of how well the model simulates water movement and root growth these hydrologic complex soils. As discussed, vertic texture contrast soils change, with factors such as soil strength and cracking altering throughout the growing season. Can APSIM account for these complexities and if not, are there parameters within the model that are able to be adapted in order to improve the simulation of root and crop growth on these soils?

### **3.5 Conclusion**

Barley root exploration in texture contrast soils with vertic subsoils mostly occurred through shrinkage cracks. Even when soils were waterlogged and soil cracks closed, roots still preferred to grow through the closed shrinkage cracks. This suggests that even at saturation the penetration resistance of the soil matrix restricted root elongation. Comparison between the rainfed and optimum treatments showed that strategic irrigation increased both the depth of root elongation and facilitated limited growth of roots from the shrinkage cracks into the soil matrix, which was not observed in the rainfed treatment.

Results from this experiment have demonstrated that application of as little as 37 mm of water applied strategically over a whole cropping season can significantly influence root depth and distribution, and ultimately crop yield. Furthermore, results demonstrated that establishing a well developed rooting pattern in what is considered a difficult soil to crop is achievable. Understanding the physical characteristics of vertic texture contract soils and the soil/root relationship is critical to developing a strategic irrigation strategy and in turn managing limited available water.

## **4.0 Chapter 4 – Modification of APSIM parameters to improve simulation of barley growth in texture contrast soils**

### **4.1 Introduction**

The Agricultural Production Systems Simulator (APSIM) is an advanced simulator of biophysical processes in agricultural systems (McCown *et al.* 1996). APSIM can be used as a decision support tool for agriculture, agribusiness and research (Carberry *et al.* 2009; Keating *et al.* 2003b). The principle advantage of APSIM over other agricultural simulation tools such as NTRM (Shaffer *et al.* 1983), HYDRUS (Šimůnek *et al.* 1999) and EPIC (Williams *et al.* 1984) is the ability to build a model combining a range of components that take into account climate, crop and soil systems and management decisions. The flexibility of these modules allows the integration of individual components to develop a framework to simulate local agricultural production systems including climatic variations over multiple years (Keating *et al.* 2003b).

The APSIM framework consists of a central simulation engine that uses a range of modules to replicate specific farming systems (Figure 4-1). This engine drives the simulation process and combines soil, crop and management components (Keating *et al.* 2003b). A range of soil types and their physical and chemical properties are assembled to build the foundation of a simulation. Within the soil water module, specific soil information such as drained upper and lower limits, initial nitrogen, and moisture are required to characterise the soil.

Crop modules include physiological traits of a range of cultivars and simulate growth, development and yield and their interaction with the soil and climate. The manager module

includes management events such as sowing, fertiliser, and irrigation and requires user input to specify the management rules of the crop.

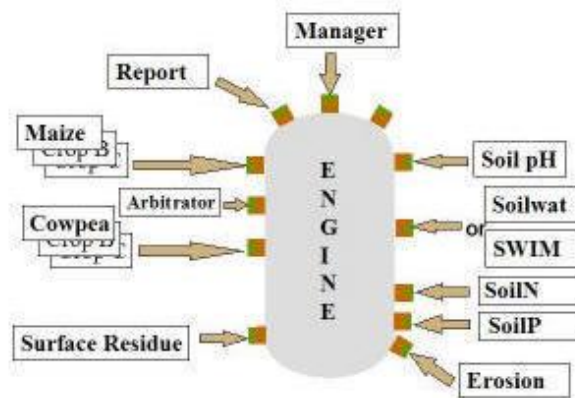


Figure 4-1. Diagrammatic representation of the APSIM framework (Keating et al. 2003b).

APSIM has been used by researchers and agronomists as one approach to benchmark performance of a range of crops, with varied success (Carberry *et al.* 2009). A database of 173 sites compiled by Carberry *et al.* (2009) demonstrated that 49% of simulated results were within 0.5 t/ha of observed yield when simulations were conducted with estimated soil characteristics. Simulation of crops parameterised with site specific data demonstrated that simulation accuracy increased to 68% within 0.5 t/ha of observed yields. Sadras *et al.* (2003) also found that predicted yield improved with the use of site-specific soil data, particularly with the addition of soil moisture.

Evans and Fischer (1999) described yield potential “as the maximum yield which could be reached by a crop in given environments, as determined, for example, by simulation models with plausible physiological and agronomic assumptions”. However, it has been widely recognised that many commercial wheat crops within Australia fall below their yield potential (Sadras and Angus 2006b; Hochman *et al.* 2009), typically due to nitrogen deficiency, biotic stresses such as weeds and disease (Angus and Herwaarden 2001a), and subsoil constraints (Zhang *et al.* 2006). Where APSIM simulations over-predict observed



yield, the simulated yield represents the potential yield of the crop (Evans and Fischer 1999). However, the APSIM model's inability to account for factors such as extreme temperatures, weeds, pests, diseases (Hochman *et al.* 2009) and lodging (Stewart *et al.* 2006) can increase the gap between potential and observed yield.

A majority of studies using APSIM as a crop modelling tool have been conducted in the low rainfall zone (LRZ) (Carberry *et al.* 2009; Hunt *et al.* 2006). Zhang *et al.* (2006) reported that average yields of wheat and canola crops in the high rainfall zone (HRZ), which includes Tasmania, were approximately 50% of APSIM simulated yields. This difference in yield was reported to be due to extensive waterlogging, physical and chemical soil constraints and limited number of adapted cultivars (Zhang *et al.* 2006). Clough *et al.* (2010) raised the issue that the simulation models that have been validated in the LRZ may not match the accuracy when applied to the HRZ due to differences in climate, soil and cultivar performance.

Local climate determines when crops are usually sown and varies between regions based on rainfall patterns. Sowing periods for cereals in the LRZ typically takes place in autumn or winter to coincide with available soil moisture and avoid frost during flowering (Angus and Herwaarden 2001a). Sowing in the HRZ occurs over a broader range to capitalise on available soil moisture and increased rainfall frequency yet avoid heavy winter rainfalls. Botwright Acuña *et al.* (2010) highlighted the potential need to develop location-specific phenological data for crop modelling in HRZ's to account for variations in cultivar base temperatures and vernalisation requirements for Tasmania.

The APSIM soil dataset contains soil types from many agricultural regions, representing their physical and chemical properties. Individual soil modules are able to be adapted by the addition of site-specific data to best represent soil characteristics. Changes in physical properties within the model can considerably alter simulation results by influencing plant available water capacity. Hydrological complex soils such as vertic, texture contrast soils present possible difficulties when running APSIM simulations. The capacity for APSIM to simulate soil water movement and storage in these soils is largely untested.

Field studies by Hardie *et al.* (2011) and Merdun *et al.* (2008) demonstrated a range of preferential flow processes in texture contrast soils, including the development of perched water tables and subsurface lateral flow during high rainfall periods (Edwards 1992; Ticehurst *et al.* 2007). The abrupt change in texture means there is a large difference in the permeability of the two soil horizons. The slow permeability of the B horizon and the small water holding capacity of the A horizon makes the soils very prone to waterlogging (Tennant *et al.* 1992). In vertic clay soils, crack formation increases as soil dries, which become preferential pathways for water and roots, but may also increase the loss of water and water soluble nitrate through deep drainage (Turtola and Paanjanen 1995). Desiccation of clay soils also decreases the rate of root growth through the increase in penetration resistance (Clark *et al.* 2003).

Although APSIM may not account for the hydraulic complexities of vertic, texture contrast soils, there are factors within the model that can be adapted to better simulate root-soil interactions. Modifying root growth functions in APSIM can be conducted by altering the water extraction (KL) and root exploration (XF) factors. KL controls the ability of roots to extract water from a soil layer and varies with crop type depending on the plant's root

architecture and ability to extract moisture from the soil. KL is thus effectively a measurement of root density within the soil layer (Manschadi *et al.* 2006). The XF factor is the capacity at which roots are able to vertically grow thorough a soil layer. Within APSIM a default XF factor of 1 simulates unimpeded root growth. Conversely, a XF value of 0 means that the layer cannot be penetrated by roots and vertical root growth ceases. XF is a useful tool to impose restrictions on root growth such as chemical restraints or hard pans.

This chapter aims to (I) simulate within APSIM the field experiment discussed in chapter 2, by comparing observed and predicted growth, yield, and components of yield, (II) incorporating root data represented in Chapter 3 with the aim of presenting a method to improve the simulation of barley growth and development on texture-contrast soils in the high rainfall zone, (III) validation using data from Matuszek (2009) and an experiment conducted in 2009/10 on the same soils (Chapter 2 and 3).

## 4.2 Materials and methods

### 4.2.1 *Experimental sites*

The 2008/09 experiment (Matuszek 2009) was conducted at the University Farm, Cambridge (42°50'S, 147°31'E) Tasmania. The soil type was a texture contrast with sandy loam top soil and below 20 cm a subsoil dominated by clay with high smectite content (Holz 1994). Barley, cv. Gardner was sown on 18 July 2008 at 100 kg/ha in plots 20 m long x 5.7 m wide and sown to a target depth of 40 – 50 cm with a row spacing of 180 mm.

For full details of experimental site, design and plant sampling for the 2009/10 and 2010/11 experiments, refer to Chapter 2.

### 4.2.2 *Soil characterisation*

Soil cores were taken prior to sowing and sent to CSBP Laboratories for chemical analysis including nitrate nitrogen, ammonium nitrate and organic carbon for each horizon (Table 4-1). Soil moisture was measured by gravimetric analysis at 105°C at 10-cm depth intervals from the soil surface (Table 4-1).

The soil lower limit (LL15) -1500 kPa was determined using a pressure plate apparatus (McKenzie *et al.* 2002). The plate was immersed in de-aired distilled water for 24 hours. Once in the chamber, <2 mm dried soil samples from each horizon were placed in rings on the plate surface and allowed to wet up for 48 hours. Equilibrium at -1500 kPa was achieved after nine days, samples were removed, weighed, oven dried at 105 °C for 24 hours and weighed again for determination of gravimetric soil moisture content.

Drained upper limit (DUL) or field capacity was measured using ceramic suction plates at a pressure of -10 kPa. Intact soil cores rings were sampled from each horizon, levelled at each end and placed on the suction plate. Once water flow attained equilibrium, the cores were weighed, oven dried at 105 °C for 48 hours and weighed again. Bulk density was assessed from the cores used to determine DUL and LL15 on a volumetric basis (Table 4-2).

Soil moisture was continuously monitored using capacitance-based Sentek EnviroSCAN Solo probes mounted in three PVC access tubes installed in each plot after emergence in the 2010/11 experiment. The EnviroSCAN probes had eight sensors located at depths of 10, 20, 30, 40, 50, 70, 90 and 110 cm. Data were logged at 10 minute intervals.

#### 4.2.3 *Root sampling*

Following harvesting of the 2009/10 experiment, ten 45mm diameter soil cores were obtained using a hydraulic push auger to a depth of 1 m. The cores were cut into 10 cm sections and root number was determined using the core-break method (van Noordwijk *et al.* 2000). The cores were weighed and placed in an oven at 105°C for 48 hours and reweighed to determine water content and bulk density.

Vertical root growth throughout the growing season was approximated by assessing diurnal soil moisture readings from the EnviroSCAN probes. In the 2010/11 experiment (Jabro *et al.* 2005). Root presence was recorded when a sensor began to demonstrate a strong diurnal fluctuation in soil water content. Evidence of diurnal fluctuations, rather

than a net decrease in soil moisture, was used to determine root presence to discount the possibility of capillary rise from roots higher in the profile.

As described in section 3.2.2, pits were excavated surrounding the EnviroSCAN tubes. A 1 m<sup>2</sup> grid with 10-cm cells was placed on the soil and roots were counted in each cell. Roots situated within cracks were excluded. Excavation was conducted at 5, 10, 20, 30, 40, 50, 70, 90, and 110 cm soil depths or until roots were no longer present. Gravimetric soil moisture content was determined from a soil sample collected from each cell. Penetration resistance was recorded with a Rimik CP20Cone Penetrometer in every second cell.

#### 4.2.4 2009/10 soil profile analysis

Physical properties of the soil profile in the 2009/10 experiment shown in Figure 4-2 and describes using Isbell (2002) as follows:

A1: 0-17 cm; Very dark brown (10YR 2/2 dry); loamy sand; weak subangular blocky structure; loose consistency (dry); few pores; many fine – medium barley roots; sharp smooth boundary.

B21: 17-43 cm; Dark yellowish brown (10YR 3/4); light clay; coarse 200 – 250 mm prismatic structure; very strong consistence (dry); many 2 – 7 mm strong brown (7.5YR 5/8) mottles; many fine – medium barley roots primarily located between peds; few pores; few large vertical 20 mm width few fine horizontal cracks; gradual smooth boundary.

B22: 43-70 cm; Olive brown (2.5Y 4/3); light clay; weak to moderate structure decreasing with depth; strong consistency (moist); few indistinct mottles; few 10 – 15 mm rounded gravel (Fe) and charcoal coarse fragments; moderate amount of fine barley roots; few fine pores; large vertical cracks 10-20 mm width to 60 cm depth; gradual smooth boundary.

B23: 70-97 cm; Dark olive brown (2.5Y 3/3); light clay; weak structure; strong consistency (moist); many dark reddish grey (2.5YR 5/1) mottles; moderate rounded – coarse dispersed 5 – 40 mm gravel fragments; moderate amount of fine barley roots; few fine pores; gradual smooth boundary.

B24: 97-100 cm; Yellowish brown (10YR 5/8); light clay; weak structure; strong consistency (moist); moderate 5 – 20 mm grayish brown (10YR 5/2) mottles; common rounded – coarse 5 – 20 mm gravel fragments (Fe); few fine barley roots to 130 cm depth; few fine pores, clear smooth boundary.

B3: 150+ cm; Olive brown (2.5Y 4/3); sandy light clay; weak structure: strong consistency (moist); common 2 – 10 mm gray (2.5Y 5/1) mottles; many rounded 40 – 80 mm fragments.

For soil profile of the 2010/11 experiment, see section 3.2.3 in Chapter 3.



Figure 4-2. Soil pit from which the soil profile analysis was conducted after harvest of 2009/10 field trial and described using Isbell (2002).

#### 4.2.5 *Saturated hydraulic conductivity*

Saturated hydraulic conductivity design was based on Amoozegar and Warrick's (1986) method with a constant head parameter. However, the flow cell was designed to encase the core horizontally rather than vertically (Figure 4-3). The soil core was horizontally aligned to improve the accuracy of hydraulic conductivity measurements. A level reservoir was set



10 mm above the height of the outlet to give a constant head of 0.01 kPa. Water was collected in a beaker and gravimetrically measured. Hydraulic conductivity was calculated using the equation as an adaptation of Darcy's Law ( $K = VL/At \Delta H$ ). Following root sampling, four cores at each horizon were sampled from the optimum treatment soil pit. Prior to placement in the flow cell, cores were saturated in a 0.01 M  $\text{CaCl}_2$  solution. Excess soil caused by swelling was removed to create a level surface, dried at 105 °C and weighed.

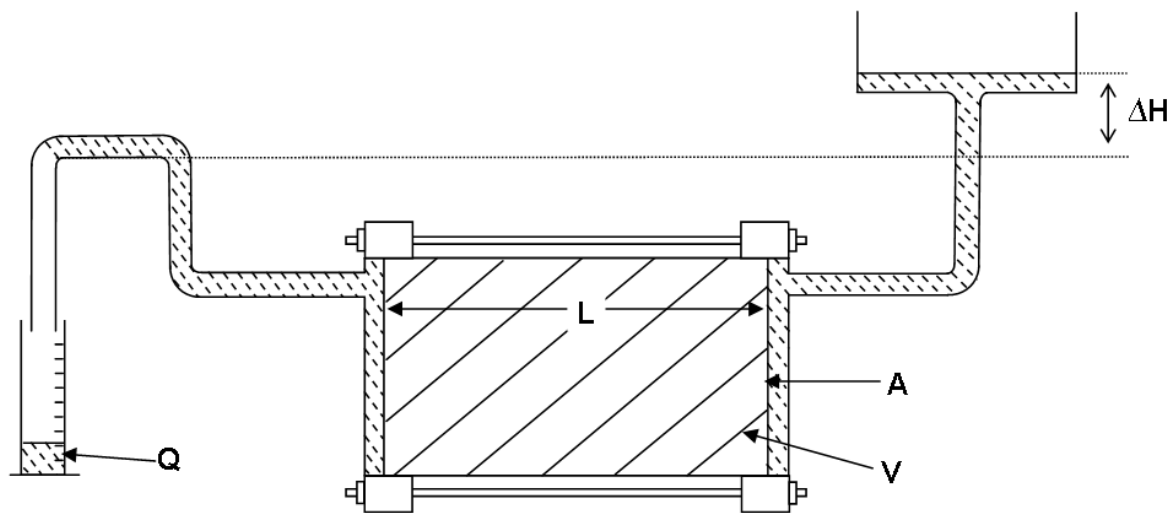


Figure 4-3. Modified Amoozegar and Warrick (1986) design used to derive hydraulic conductivity measurement for APSIM parameterisation.  $\Delta H$  denotes the total difference in head,  $A$  is the cross-sectional area,  $V$  is the total volume of the core,  $L$  is the length of the core and  $Q$  is the quantity of water collected.

#### 4.2.6 APSIM parameterisation

Simulations were conducted in APSIM Version 7.5. Climate data were obtained from a data drill file accessed via the silo climate website (<http://www.longpaddock.qld.gov.au>) based on site coordinates (42°77'S, 147°42'E). Weather data included daily radiation, maximum and minimum temperature, rain, evaporation, and vapour pressure.

The APSIM crop module used was APSIM-Barley, configured with SOILN, SOILWAT, and SURFACEOM. A brown Sodosol (N0781) was selected from the APSIM soil library as the base site soil module. Site specific data for 2010/11 was entered to parameterise the physical characteristics of the soil. These included bulk density (BD), drained upper limit (DUL), drained lower limit (LL15), saturation (SAT) and particle size. Soil depths were separated into 10-cm layers to reflect the positioning of the EnviroSCAN sensors. Soil module (N0781) included only crop-specific soil wheat characteristics for wheat; consequently KL parameters (/day) were changed to reflect the values of barley consistent with other soil modules containing similar soil parameters. Soil sample data taken prior to sowing were added to specify initial soil moisture, nitrogen as nitrate and ammonia, total organic carbon, pH (1:5 water) and electrical conductivity. A management routine was included to reset water, nitrogen and surface organic matter prior to each simulation.

The simulated barley cultivar selected was gairdner\_TAS. Gairdner\_TAS was developed by Botwright Acuña *et al.* (2010) to suit APSIM simulations under Tasmanian climatic conditions by revising vernalisation sensitivity, photoperiod sensitivity and thermal time. Experimental information inputted into APSIM simulations are detailed in Chapter 2, experiment 2010/11. This includes sowing date, rate and depth, fertiliser type and application and irrigation depth and date.

Table 4-1. Initial gravitational soil moisture (SM), nitrate (NO3), ammonium (NH4) and total organic carbon (OC) from data collected from the field site, used to parameterise APSIM.

Soil depth intervals (cm)	Rainfed				Optimum				Waterlogged			
	SM (mm/mm)	NO3 (kg/ha)	NH4 (kg/ha)	OC (Total %)	SM (mm/mm)	NO3 (kg/ha)	NH4 (kg/ha)	OC (Total %)	SM (mm/mm)	NO3 (kg/ha)	NH4 (kg/ha)	OC (Total %)
0-10	0.226	72	3	2.530	0.234	55	2	2.120	0.250	60	3	2.090
10-22	0.181	72	3	2.530	0.161	55	2	2.120	0.178	60	3	2.090
22-25	0.189	17	2	1.340	0.182	11	2	1.160	0.186	16	2	0.800
25-35	0.180	10	2	1.340	0.204	12	1	0.460	0.194	14	4	0.790
35-45	0.171	10	2	1.340	0.228	12	1	0.460	0.247	14	4	0.790
45-55	0.155	10	2	1.340	0.267	12	1	0.460	0.268	14	4	0.790
55-65	0.146	15	2	0.370	0.283	13	4	0.220	0.273	16	1	0.320
65-75	0.161	15	2	0.370	0.268	13	4	0.220	0.269	16	1	0.320
75-85	0.170	15	2	0.370	0.256	13	4	0.220	0.288	16	1	0.320
85-95	0.165	16	5	0.360	0.255	10	3	0.910	0.214	10	4	0.160
95-105					0.219	10	3	0.910	0.199	10	4	0.160
105-115					0.197	10	3	0.910	0.164	10	4	0.160
115-125					0.170	6	3	0.130				
125-135					0.150	6	3	0.130				

Table 4-2. Soil data from lab testing across all treatments as entered into APSIM simulations, including bulk density (BD), volumetric soil water of air dried samples (Air dry), samples pressurised to -1500 kPa (LL15), samples drained to -10 kPa (DUL) and saturation samples. APSIM derived data includes barley lower limit (Barley LL) and plant available water capacity (PAWC). Electrical conductivity and (EC) and pH were derived from start of season sampling.

<b>Soil depth intervals (cm)</b>	<b>BD (g/cc)</b>	<b>Air dry (mm/mm)</b>	<b>LL15 (mm/mm)</b>	<b>DUL (mm/mm)</b>	<b>SAT (mm/mm)</b>	<b>Barley LL (mm/mm)</b>	<b>PAWC (mm)</b>	<b>EC (1:5 dS/m)</b>	<b>pH (1:5 water)</b>
<b>0-10</b>	1.36	0.045	0.073	0.220	0.457	0.090	13.0	0.221	7.4
<b>10-22</b>	1.36	0.045	0.073	0.220	0.457	0.180	15.6	0.221	7.4
<b>22-25</b>	1.66	0.024	0.025	0.280	0.380	0.253	0.8	0.116	5.8
<b>25-35</b>	1.66	0.250	0.252	0.367	0.410	0.253	11.4	0.090	5.4
<b>35-45</b>	1.66	0.250	0.252	0.367	0.410	0.253	11.4	0.090	5.4
<b>45-55</b>	1.66	0.250	0.252	0.367	0.410	0.253	11.4	0.090	5.4
<b>55-65</b>	1.73	0.226	0.266	0.350	0.371	0.226	12.4	0.184	5.8
<b>65-75</b>	1.73	0.226	0.266	0.350	0.371	0.226	12.4	0.184	5.8
<b>75-85</b>	1.73	0.226	0.266	0.350	0.371	0.226	12.4	0.184	5.8
<b>85-95</b>	1.61	0.250	0.253	0.382	0.414	0.271	11.1	0.215	6.6
<b>95-105</b>	1.61	0.250	0.253	0.382	0.414	0.271	11.1	0.215	6.6
<b>105-115</b>	1.61	0.250	0.253	0.382	0.414	0.271	11.1	0.215	6.6
<b>115-125</b>	1.61	0.250	0.253	0.382	0.414	0.271	11.1	0.278	7.6
<b>125-135</b>	1.61	0.250	0.253	0.382	0.414	0.271	11.1	0.278	7.6

#### 4.2.7 *APSIM modelling- exploration factors*

Separate simulations were run for each soil moisture treatment with a range of KL and XF options. Simulations were first run with default APSIM parameters ( $KL_D/XF_D$ ) of 0.07 and 1 respectively.

Simulations were rerun in which KL parameters were adjusted according to the root number curve derived in Figure 3-4 Chapter 3, with 0.07 equal to the maximum root density across the three treatments (optimum 30 cm). XF parameters remained unchanged and the simulation was identified as  $KL_A/XF_D$ .

Simulations were repeated with  $KL_A$  values and the addition of refined XF parameters fitted to the same root curve of  $KL_A$  ( $KL_A/XF_A$ ). The layer with the greatest root density of each treatment was considered the maximum rate of root growth and assigned the XF value of 1. All root counts within that treatment were calculated as a fraction of 1.

Simulations containing  $KL_D/XF_A$  parameters are not presented, as they did not alter simulation outputs.

KL and XF parameters can be altered to apply specific experimental root or soil data to improve crop simulation in a variety of methods. For example, Lilley and Kirkegaard (2007) adapted APSIM XF parameters in their study to account for increasing soil strength by decreasing root penetration rate as PAW decreased once it fell under 25%. In this experiment the soil mechanisms reducing root growth rates were increased penetration resistance in the case of the rainfed treatment and root death in the upper subsoil in the waterlogged treatment. Applying the same root density curve as used in the KL parameters

to the XF parameters can be used to account for these influences on root growth. While these parameters are not a direct measurement of soil strength or waterlogging, they are an estimation of the impact that these two factors can have on root growth in vertic texture contrast soils. However, these parameter adaptations within the current version of APSIM are static and do not change over the season, only provide an empirical method of determining restrictions on root growth.

Table 4-3. APSIM default values of water extraction ( $KL_D$ ) and root exploration ( $XF_D$ ) and adapted values ( $KL_A/XF_A$ ) used for adapted APSIM simulations for each treatment. All  $KL_A$  values are represented as a fraction of the root count taken at the optimum treatment at 25-30 cm from the 2010/11 field experiment. All  $XF_A$  values are a fraction of the individual treatments maximum root count.

Soil depth intervals (cm)	APSIM default		Rainfed		Optimum		Waterlogged	
	$KL_D$ (/day)	$XF_D$ (0-1)	$KL_A$ (/day)	$XF_A$ (0-1)	$KL_A$ (/day)	$XF_A$ (0-1)	$KL_A$ (/day)	$XF_A$ (0-1)
0-10	0.07	1.0	0.060	1.000	0.052	0.743	0.030	0.701
10-22	0.07	1.0	0.057	0.950	0.051	0.734	0.032	0.763
22-25	0.07	1.0	0.048	0.792	0.053	0.763	0.041	0.973
25-35	0.07	1.0	0.042	0.748	0.070	1.000	0.027	0.810
35-45	0.07	1.0	0.032	0.703	0.049	0.696	0.042	0.647
45-55	0.05	1.0	0.019	0.539	0.039	0.558	0.039	1.000
55-65	0.05	1.0	0.015	0.434	0.025	0.497	0.027	0.925
65-75	0.05	1.0	0.012	0.351	0.022	0.436	0.026	0.890
75-85	0.05	1.0	0.008	0.267	0.020	0.397	0.017	0.855
85-95	0.05	1.0	0.004	0.086	0.018	0.357	0.008	0.255
95-105	0.05	1.0			0.012	0.236	0.005	0.156
105-115	0.05	1.0			0.006	0.114	0.002	0.058
115-125	0.05	1.0			0.004	0.075		
125-135	0.05	1.0			0.002	0.035		

### 4.3 Results

The first set of results (section 4.3.1) relates to crop growth and root data represented the 2010/11 experiment in Chapter 2 and 3 with the aim of presenting a method to improve the simulation of barley growth and development on texture-contrast soils in the high rainfall zone. Section 4.3.2 are results of the APSIM validation using data from (Matuszek 2009) and an experiment conducted in 2009/10 on the same soils.

#### 4.3.1 2010/11

##### 4.3.1.1 *Observed vs. simulated crop growth*

Simulated crop phenology was within 2 and 3 days of observed values across all three treatments at 64 and 88 DAS (Table 4-4). Predicted leaf area index (LAI) at 64 DAS was overestimated by an average of 52%, particularly for the rainfed and optimum treatments. In contrast, predicted LAI at 88 DAS was underestimated for rainfed and waterlogged, but overestimated for the optimum treatment. Yield and grain weight were overestimated, whereas grain number was underestimated in all three treatments. Overall, APSIM does not accurately simulate grain size and weight.

Table 4-4. Comparison of observed and default APSIM simulated phenology, leaf area index (LAI), yield and components of yield. The simulated/observed (sim/obs) ratio is included to evaluate initial model performance.

	Stage 30 (DAS)	Stage 60 (DAS)	LAI 64 DAS	LAI 88 DAS	Yield (kg/ha)	Grain No. (/m <sup>2</sup> )	Grain Wt (mg)
<b>Rainfed</b>							
<b>Observed</b>	64	88	2.8	2.9	4860	14404	51
<b>Simulated</b>	67	90	5.2	2.7	6716	8989	65
<b>Ratio (sim/obs)</b>	1.05	1.02	1.86	0.93	1.38	0.62	1.27
<b>Optimum</b>							
<b>Observed</b>	64	88	4.0	5.1	6380	17688	50
<b>Simulated</b>	67	90	6.4	5.6	8361	11190	65
<b>Ratio (sim/obs)</b>	1.05	1.02	1.60	1.10	1.31	0.63	1.30
<b>Waterlogged</b>							
<b>Observed</b>	64	88	5.8	4.3	5480	17736	38
<b>Simulated</b>	67	90	6.4	3.1	8870	11872	65
<b>Ratio (sim/obs)</b>	1.05	1.02	1.10	0.72	1.62	0.67	1.71

#### 4.3.1.2 Observed vs. predicted root growth over time

In rainfed simulations, changes in root depth were very similar containing  $KL_D/XF_D$  and  $KL_A/XF_D$  parameters (Figure 4-3a). Both overestimated growth rate early in the season. The addition of an adapted XF parameter ( $KL_A/XF_A$ ) reduced the root growth rate throughout the season, improving the comparison with the observed data; however, final root depth was slightly underestimated by 100 mm.

Waterlogged simulations containing  $KL_D/XF_D$  parameters overestimated root depth over the season (Figure 4-3c).  $KL_A/XF_D$  simulations followed the same early season root growth pattern however, plateaued 15 days earlier than  $KL_D/XF_D$  resulting in a reduced final root depth that was similar to the observed depth. Similarly to the rainfed treatment, the simulations containing  $KL_A/XF_A$  parameters reduced root growth, improving the comparison to observed data but underestimated the final root depth.



Simulations of the optimum treatment containing  $KL_D/XF_D$  and  $KL_A/XF_D$  parameters accurately simulated the change in root depth (Figure 4-3b). The addition of an adapted XF parameter ( $KL_A/XF_A$ ) poorly simulated root growth, underestimating root growth rate and final depth.

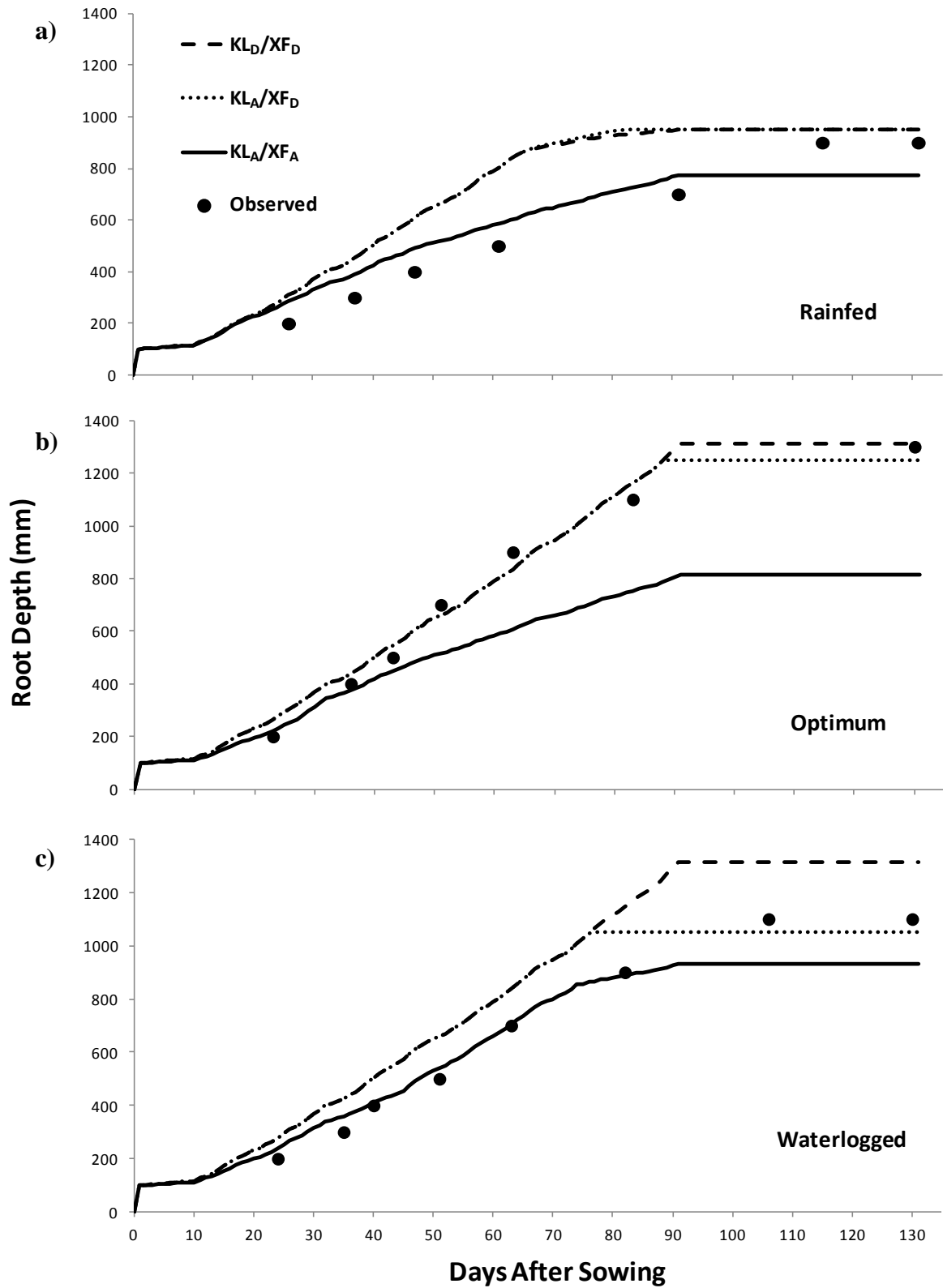


Figure 4-4. Comparison of observed and simulated APSIM root growth of rainfed, optimum and waterlogged treatments derived from simulations containing default KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, adapted KL parameters ( $KL_A$ ) and adapted KL ( $KL_A$ ) and XF ( $XF_A$ ) parameters.

#### 4.3.1.3 *Observed vs. predicted leaf area index over time*

LAI correlations between observed and simulated data (Figure 4-5) are limited by the lack of observed data points. However, the two data points demonstrated that no one simulation approach adequately replicated the observed LAI for the entire growing season.

Initial simulated LAI ( $KL_D/XF_D$ ) was overestimated across all treatments at 64 DAS but was very similar to measurements taken at 88 DAS in the rainfed and optimum treatments, with the waterlogged treatment still demonstrating a slight overestimation.

$KL_A/XF_D$  simulations reduced the disparity between observed and simulated LAI in all treatments at 64 DAS by decreasing the rate of development. However, the decrease in LAI development led to an underestimated LAI at 88 DAS.

The addition of an adapted XF parameter ( $KL_A/XF_A$ ) led to a reduction of LAI throughout the season across all treatments, most notably in the optimum treatment, but followed a very similar pattern to the  $KL_A/XF_D$  simulation. The  $KL_A/XF_A$  simulations delivered the most accurate comparison in LAI at measurements taken at 64 DAS however, also gave the greatest difference in simulated and observed LAI at 88 DAS.

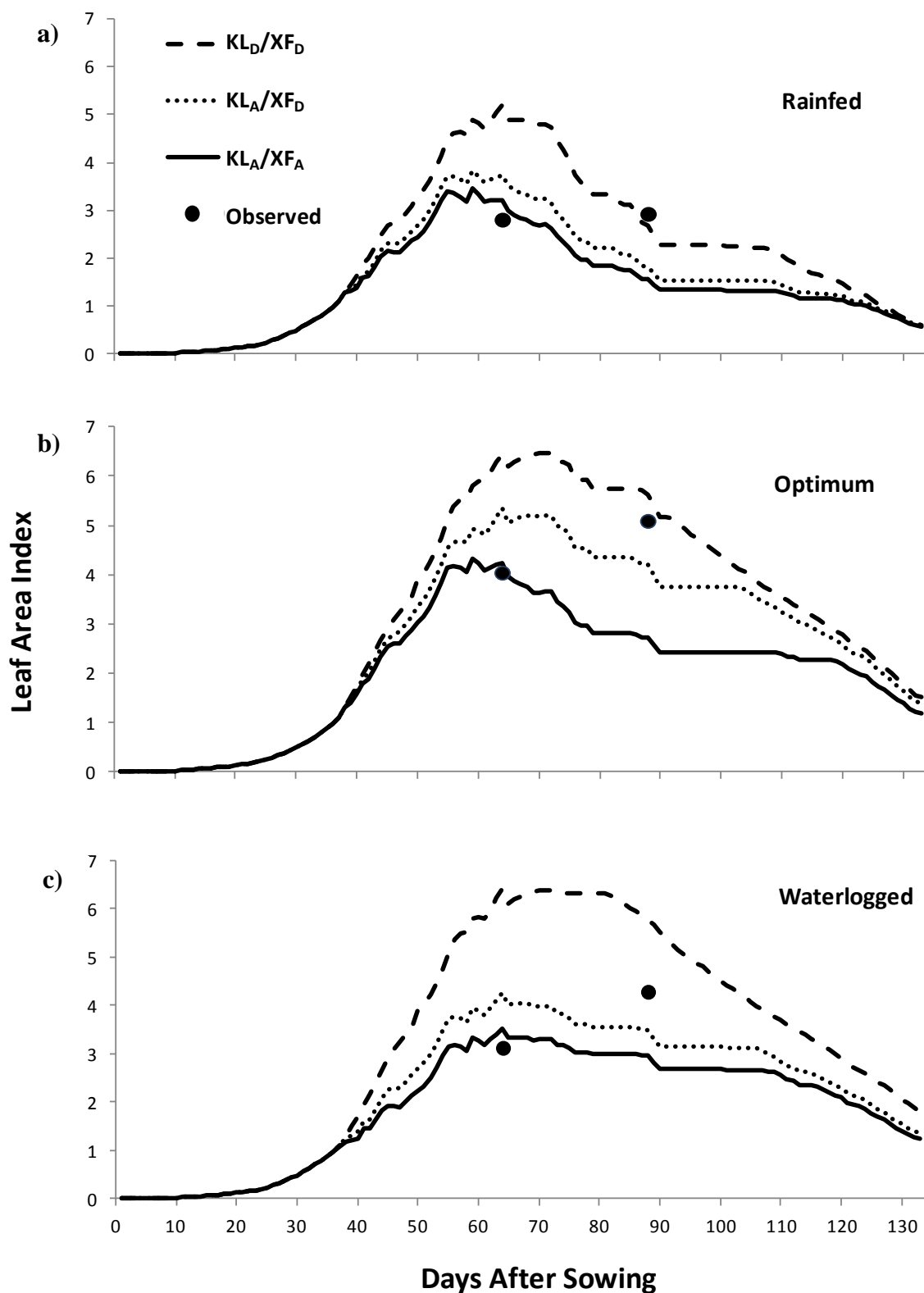


Figure 4-5. Comparison of observed and simulated APSIM leaf area index (LAI) of rainfed, optimum and waterlogged treatments in season 2010/11 derived from simulations containing default KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, adapted KL parameters ( $KL_R$ ) and adapted KL ( $KL_R$ ) and XF ( $XF_R$ ) parameters.

#### *4.3.1.4 Observed vs. predicted yield and yield components*

For all three treatments, simulations containing  $KL_A$  parameters resulted in lower yields than for  $KL_D$  simulations, with the greatest reduction of yield of almost 2000 kg/ha in the waterlogged treatment. The rainfed and optimum treatments had smaller reductions in yield of 1264 and 705 kg/ha respectively.

Treatment simulations run with  $KL_A/XF_A$  parameters all displayed further reductions in yield compared with simulations containing only adapted KL parameters. The rainfed and waterlogged treatment yield reduced by approximately 500 kg/ha and optimum yield reduced by a further 1200 kg/ha. Rainfed and optimum simulations containing  $KL_A/XF_A$  were within 2% of the observed yields, whereas the waterlogged yield was 15% greater.

Components of barley yield included grain number and grain weight. The addition of  $KL_A/XF_A$  to simulations continued to reduce simulated grain number, with the greatest reduction observed in the waterlogged treatment (Figure 4-5a). All APSIM simulations containing the  $KL_D$ ,  $KL_A$ ,  $XF_D$ , and  $XF_A$  parameters displayed a constant grain weight of 65 mg/grain across all treatments (Figure 4-5b).

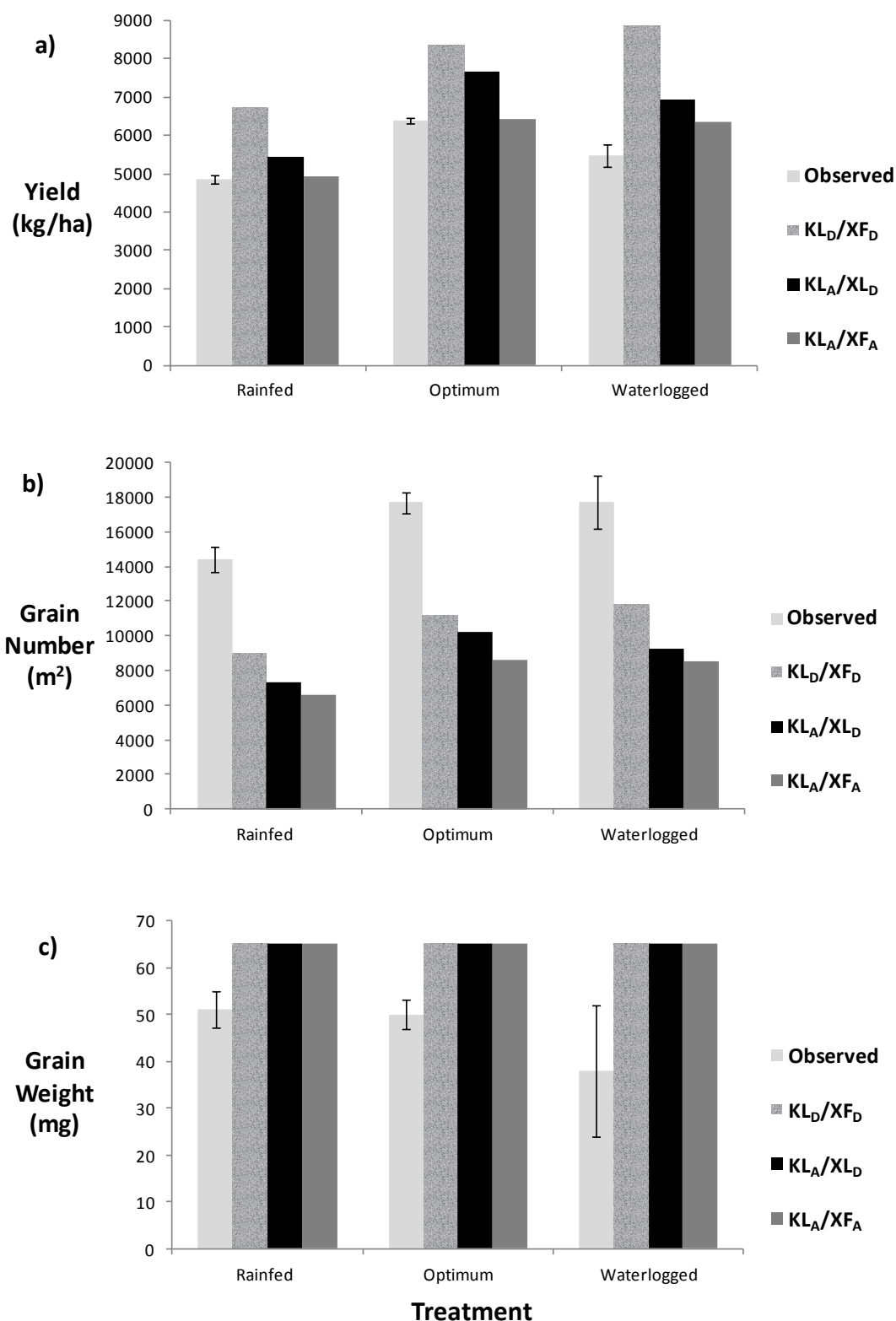


Figure 4-6. Comparison of observed and simulated APSIM yield (a), grain number (b) and grain weight (c) derived from simulations containing default APSIM KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, adapted KL parameters ( $KL_A$ ) and adapted KL ( $KL_A$ ) and XF ( $XF_A$ ) parameters. Error bars for observed grain number and weight represent  $\pm 1$  standard error.

#### 4.3.2 *APSIM validation with 2008/9 and 2009/10*

These earlier datasets were used to validate the 2010/11 finding and simulations.

##### 4.3.2.1 *Observed vs. predicted leaf area index*

Similar to season 2010/11, LAI correlations between observed and simulated data (Figure 4-7) are limited by the lack of observed data points.

The 2008/09 season LAI all simulations displayed a similar trend from sowing to 90 DAS and notably overestimated LAI compared with observed data at 95 DAS.  $KL_A/XF_D$  and  $KL_A/XF_A$  simulations had a very similar reduction in LAI and corresponded to the observed LAI at 110 DAS. Initial simulated LAI ( $KL_D/XF_D$ ) was overestimated at both 95 and 110 DAS.

LAI in was overestimated in the 2009/10 simulations, however not to the same extent as 2008/09. ( $KL_D/XF_D$ )

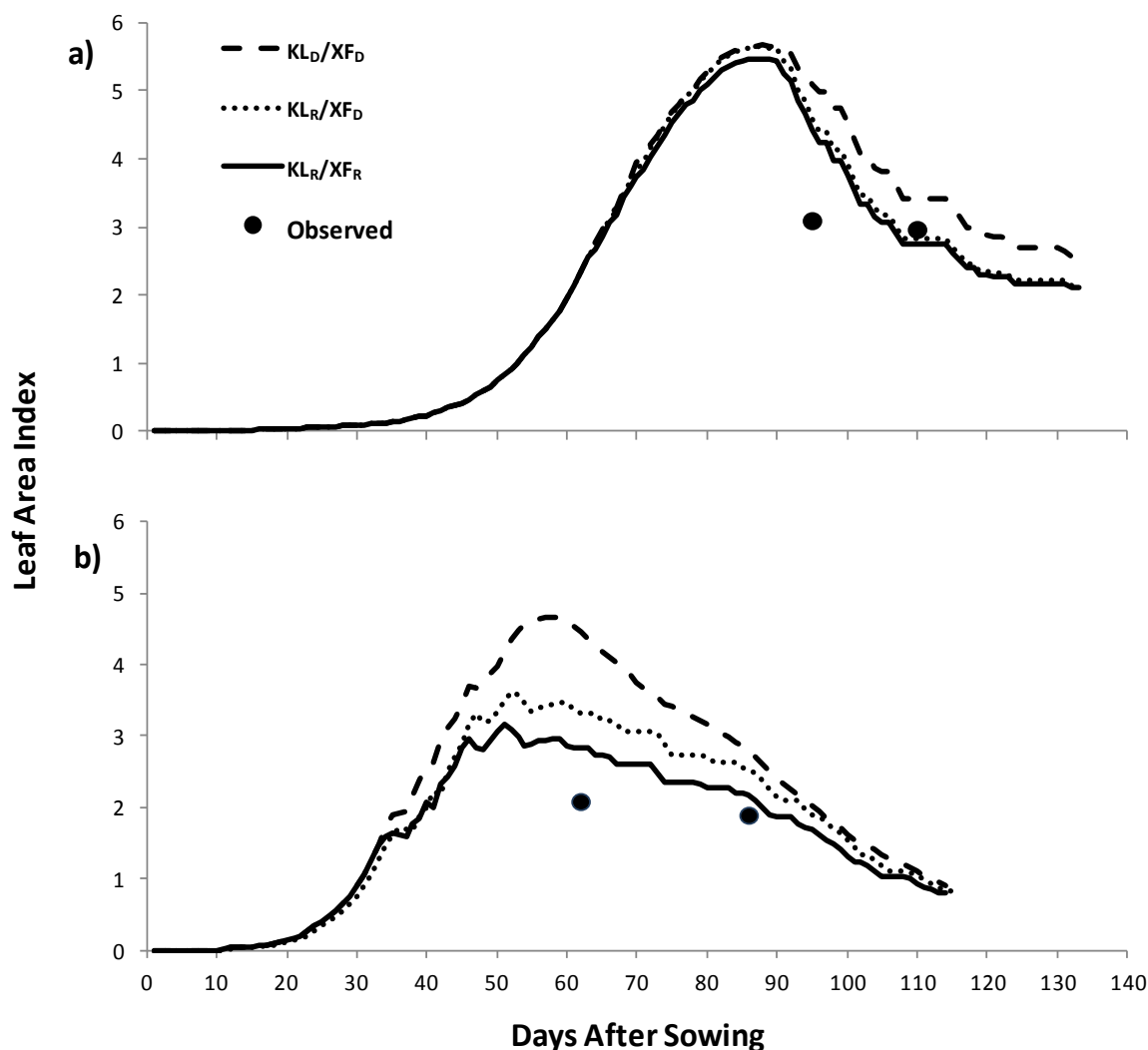


Figure 4-7. Comparison of observed and simulated APSIM leaf area index (LAI) of seasons a) 2008/09 and b) 2009/10 from simulations containing default KL ( $KL_D$ ) and XF ( $XF_D$ ) parameters, revised KL parameters ( $KL_A$ ) and revised KL ( $KL_A$ ) and XF ( $XF_A$ ) parameters.

#### 4.3.2.2 Observed vs. predicted yield and yield components

In 2008/09 and 2009/10 experiments, simulations containing  $KL_A$  parameters resulted in lower yields than  $KL_D$  simulations, with an average reduction of yield of 916 kg/ha in the 2009/10 experiment plots. The 2008/09 experiment demonstrated a reduction in predicted yield of only 510 kg/ha (Figure 4-8a). Simulations run with  $KL_A/XF_A$  parameters all displayed slight reductions in yield compared with simulations containing only adapted



KL parameters and were all within 10% of the observed yields except for plot 1 in the 2009/10 experiment.

The addition of  $KL_A/XF_A$  to simulations continued to reduce simulated grain number similarly across the three plots in the 2009/10 experiment (Figure 4-8b). All APSIM simulations containing the  $KL_D$ ,  $KL_A$ ,  $XF_D$ , and  $XF_A$  parameters displayed a constant grain weight of 65 mg/grain in both experiments (Figure 4-8c).

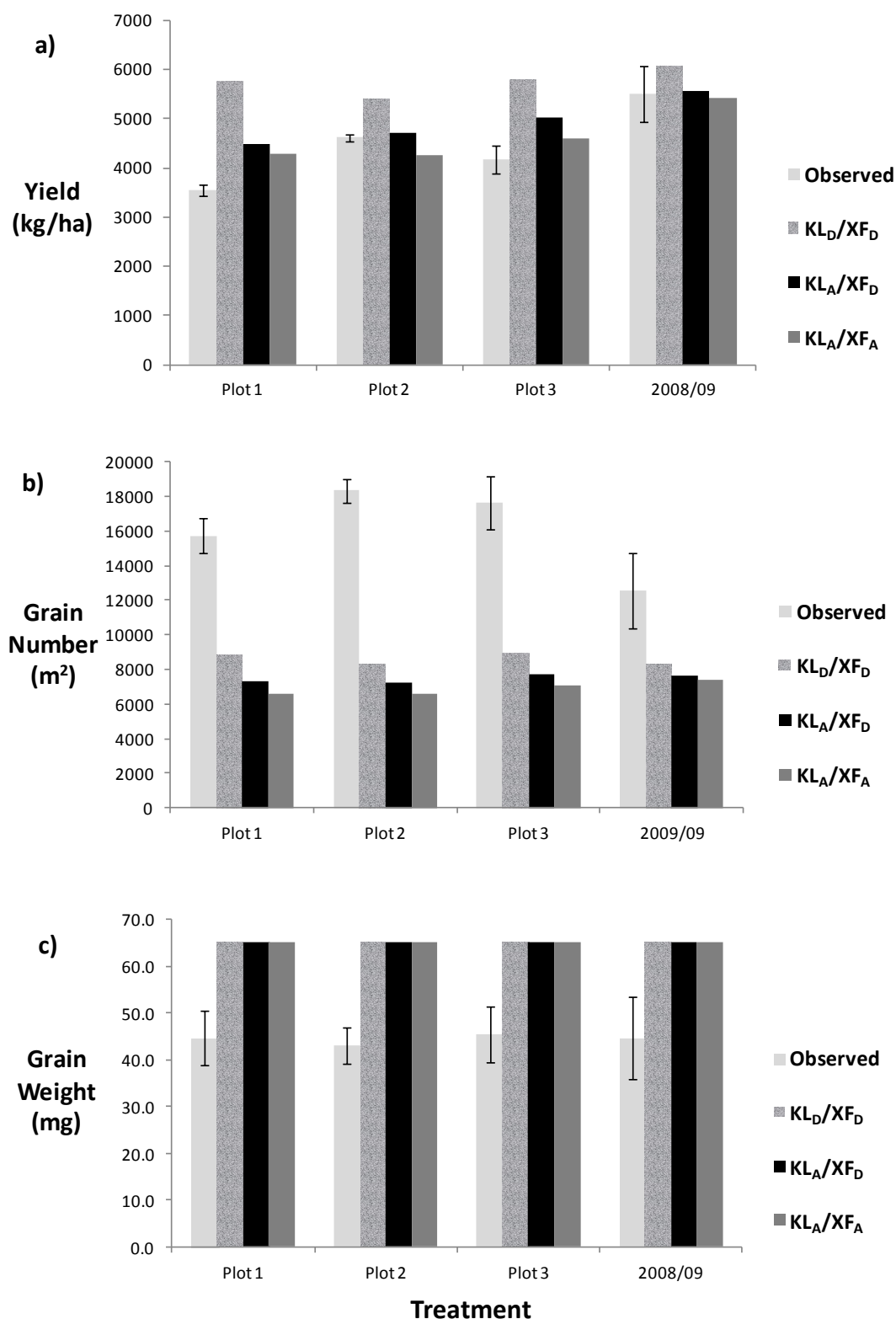


Figure 4-8. Comparison of observed and simulated APSIM yield (a), grain number (b) and grain weight (c) derived from simulations containing default APSIM KL (KL<sub>D</sub>) and XF (XF<sub>D</sub>) parameters, revised KL parameters (KL<sub>A</sub>) and revised KL (KL<sub>A</sub>) and XF (XF<sub>A</sub>) parameters. Error bars for observed grain number and weight represent  $\pm 1$  standard error.

#### 4.4 Discussion

Crop phenology refers to the physiological age and morphological appearance of the plant (Penning de Vries and van Laar 1982). It controls the partitioning and distribution of assimilates and therefore accurate simulation of crop phenology is imperative for functional crop models (Wang and Engel 1998). Phenology of a crop cultivar can vary under different climatic conditions (Tao *et al.* 2006) therefore it is important that model parameters of cultivars are specific to regional climate.

All APSIM simulations using the barley model (gairdner\_TAS) simulated the phenology of the crop comparatively well (Figure 4-5). This is due to the gairdner\_TAS being developed to account for Tasmania's milder climate and higher annual rainfall based on crop analysis by Acuña *et al.* (2010). Alterations within the model include increases in vernalisation sensitivity, photoperiod sensitivity and thermal time requirements for flowering, grain fill and maturity (Botwright Acuña *et al.* 2010). In comparison to simulations using the original Gairdner cultivar, these changes increase LAI and delay senescence, increase grain number, prolong ear development and extend grain fill.

The development of this specific barley model demonstrates the beneficial flexibility of APSIM as a crop modelling tool and the impact it has on simulated growth and yield component. However, the initial simulation displayed discrepancies between simulated and observed leaf area index, yield, components of yield and root growth within all treatments. Chapter 2 demonstrated how soil moisture can affect root number in texture contrast soils. In combination with APSIM's limited parameterisation of the hydrological characteristics of these soils and the impact that simulated water availability has on crop growth, correct simulation of root growth is vital, particularly on texture contrast soils.

#### 4.4.1 *APSIM soil/root parameterisation*

The KL parameter within the APSIM model is set for each individual soil within the soil library to account for soil diffusivity and root number (Wang and Smith 2004). The KL parameters can be altered to reflect actual experimental data such as changes in moisture and root growth and analyse how it may affect crop water uptake. For example, Zhang *et al.* (2007) estimated and adapted KL parameters for their simulations of spring wheat from soil moisture measurements taken during periods of rapid decrease in water content.

In this study the KL parameters were replaced on the basis of the root number vs. depth curve as a surrogate of water uptake within the profile (Table 4-3). Root length density is an important factor in determining water uptake by cereal crops within soil profiles (Hamblin and Tennant 1987; Manschadi *et al.* 2006). Initial simulations containing default APSIM KL and XF parameters resulted in an overestimation of crop growth, yield and particularly root depth and root growth rate (Figure 4-4 to 4-5). A reduced gap between simulated and observed yield with adapted KL parameters was due to a reduction in root exploration (Figure 4-4).

Clay soils often exhibit greater potential for water extraction due to their improved water holding capacity. However, White and Kirkegaard (2010) found wheat root growth in dense soils are often confined to pores and cracks, particularly at depths greater than 60 cm, a feature that is common in vertic texture contrast soils (Dracup *et al.* 1992). This may explain why the inclusion of treatment specific root number curves decreases actual PAW

and allowed APSIM to simulate water uptake rates based on the root distribution and depth in the profile.

While alterations to KL parameters addressed the effect of vertic texture contrast soils has on root distribution, it did not take into account root growth rate. APSIM modules adjust root growth rate by accounting for the effect of temperature, supply and demand ratios of the crop and water availability (Connolly *et al.* 2002). This is demonstrated in Figure 6 by the difference in simulated root growth rate between the rainfed and optimum treatments. Simulated and observed root growth rates in the optimum treatment were both 13.1 mm/day up to anthesis, demonstrating that APSIM is able to simulate root growth rate in an unimpeded clay soil. However, the increase in root growth of 3 mm/day in the simulated rainfed and waterlogged treatments compared with observed growth rates demonstrate that these simulations required adjusting. These differences may seem insignificant but can equate to an overestimation of 30 cm in maximum root depth over the course of a season, which Kirkegaard *et al* (2007) demonstrated can improve yields and yield components of wheat by up to 620 kg/ha, which is significant. More importantly, the increase in simulated growth rate can lead to premature use of soil water and terminal drought, therefore impacting the simulation of crop and root growth. This is evident in the root growth of the waterlogged treatment with R KL parameters. Simulated root growth prematurely ceased because PAW was reduced even though the growth rate was unchanged.

The APSIM model design allows for a mechanistic approach in simulating outputs such as yield, soil water uptake and root growth. This can include modifications in root growth rate based on penetration resistance. Da Silva and Kay (1997) developed an equation to

determine penetration resistance based on volumetric water content, bulk density, clay content and organic matter in soils with clay contents ranging between 6 and 37% and organic carbon between 9 and 39 kg/ha (Gracia *et al.* 2012). These factors are all pre-existing parameters within APSIM and may be used to develop code to evaluate the effect of soil moisture on penetration resistance. XF is currently a fixed parameter for the duration of a simulation therefore this code may generate a dynamic XF parameter based on fluctuations in soil moisture to be included in APSIM functions.

While an inbuilt function may simulate the change of soil penetration resistance, the development of cracks in the clay subsoil poses another issue for simulating root growth in vertic soils. As soil dries, crack formation within vertic soils creates preferential pathways for water (Römken and Prasad 2006; Novák *et al.* 2002) and roots (Whiteley and Dexter 1983). While functions within APSIM may be able to account for variations in penetration resistance, the formation of cracks and their influence on root architecture is more difficult to simulate.

Therefore, the use of the root number curves as a simple but effective alternative to capturing the dynamic nature of vertic texture contrast soils. While it may not fully encompass the mechanistic approach in which APSIM modules are able to operate, it roughly simulated how characteristics such as soil strength, waterlogging and crack formation have on root architecture and water uptake in a vertic texture contrast soil under variation of seasonal rainfall.

#### 4.4.2 *Yield and crop simulations*

The 2010/11 experiment demonstrated an improvement in simulated yield, LAI and components of yield with the adjusted KL and XF parameters, which was also observed in the validation simulations (2008/9, 2009/10). However, across all three experiments there were also discrepancies in crop performance under a Tasmanian climate within the simulations.

Although it is difficult to draw conclusions between observed and simulated LAI data due to limited observational data points across all years, Figure 4-5 suggest that the rate of simulated LAI development and senescence does not match that of observed barley under Tasmania's mild climate. Winter-sown crops experience milder growing conditions causing a more gradual but sustained vegetative stage compared with the Australian mainland (Russell and Mendham 1985a). Default simulations displayed a rapid rise in LAI reaching a maximum level much earlier than observed data. Adapted simulations reduced the rate of LAI development yet the crop appeared to senesce too soon and too rapidly. This suggests that some changes within the model are required to prolong the LAI green canopy of the crop.

Another parameter not well simulated was grain number. Simulated grain number in all years was underestimated in all treatments. A contributing variable effecting grain number within the barley model is stem weight. Stem weight is a determinant of grain number as water soluble carbohydrates stored within the stem are translocated into the ear during spike development (Fischer 1985). High stem carbohydrate content (Ruuska *et al.* 2006) and grain number are also associated with longer periods of stem elongation (Miralles *et al.* 2000), which is a characteristic of cereals grown in mild climates including Tasmania

(Botwright Acuña *et al.* 2011). The stem to grain weight ratio in the APSIM barley model is set at 25 grains/gram of stem. The observed grains to stem weight ratio was 35 grains/gram of stem across all the treatments suggesting that the model was under predicting the assimilation of stored carbohydrates within the stem to the ear during grain fill. Adjusting the stem weight to grain ratio from 25 to 35 increased simulated grain number, however grain number was still between 10 and 35% less than the observed data. It also overestimated yield by a further 30% in the  $KL_R$  &  $XF_R$  simulations, suggesting that other physiological changes within the model are required to increase grain number.

Grain weight was another component of yield that was poorly simulated across all years with overestimated in all treatments and attained a maximum weight of 65 mg and would have increased if not for the default limit set in the APSIM barley model. In cereals, grain weight is determined by the source/sink relationship of components of yield such as number of ears and grain/ear (García del Moral *et al.* 1991; Simane *et al.* 1993). The change in grain to stem weight ratio attributed to a reduction in grain weight in the rainfed treatment. A simple method of reducing simulated final grain weight is to limit the maximum grain weight attained by the crop within the model. However, it is a rather crude method of controlling grain weight and does not address the issue of poor partitioning of assimilates within the ear.



## 4.5 Conclusion

APSIM poorly simulated a number of parameters of barley grown on Tasmanian vertic texture contrast soils, most notably overestimation of yield and root growth. Adapted exploration factor and water extraction parameters based on detailed root density curves improved the comparison between observed and simulated yields, in particularly vertic soils that exhibit barriers limiting root growth such as high penetration resistance and waterlogging. These adaptations do not encompass the dynamic nature of cropping components within APSIM, yet are a simple method of simulating root growth and water uptake by accounting for the complex effect of vertic texture contrast soil on root growth such as high soil strength and crack formation. The changes to KL and XF parameters however, failed to improve simulated crop components including LAI, grain number and grain weight. It has been recognised by Acuña et al. (2010) that APSIM requires cultivar adaptations to simulate barley growth in Tasmania's mild, high rainfall climate. However, further detailed field research is required in order to encompass the growth and development of crop components that may differ in the HRZ compared to LRZ's.

## 5.0 General discussion

### 5.1.1 Overview

The general consensus of growers in Tasmania regarding root growth on vertic texture contrast soils is that annual crops, including barley, only utilise the upper 30 – 40 cm of the soil (Gunn *et al.* 2010, pers. comm.) Preliminary data demonstrated that root growth can reach depths of 90 cm in a wet year, or under irrigation in variable climatic conditions. Experiment were set-up to determine which physical factors in the vertic texture contrast soils have the biggest influence on root growth and architecture, impact on root depth and WUE.

It was demonstrated that root depth and architecture could be manipulated using strategic irrigation of only 37 mm based on soil moisture monitoring and observed soil conditions such as cracking. Roots under rainfed conditions followed a steady growth rate through the soil, and were until restricted by an increase in soil strength as the season progressed. Strategic irrigation increased root exploration under irrigation, in contrast, reduced soil strength during waterlogging caused plant stress and death of the nodal roots. Ready access of roots to water removed the impetus for root exploration by the crop. An abundance of cracks was demonstrated to play an important role in the exploration of roots into the subsoil by providing preferential pathways for root growth. However, these observations were made at the end of the season, whereas the relationship between soil moisture, soil strength and crack abundance fluctuated during the season.

The relationship between root growth and soil characteristics such as soil strength and cracking are important to consider when crop modelling in vertic texture contrast soils. These complexities are difficult to replicate within the APSIM model and can lead to

poorly simulated root growth and have a large influence on simulated crop water availability, which can follow on to crop growth and yield. The thesis determined how crops grown under varied soil moisture performed in APSIM and to see whether the root growth in the model matched what was observed in the vertic texture contrast soils. In the case of poorly simulated yield and crop growth the aim shifted to adapting root factors in APSIM to improve the simulator's capability to model root growth within vertic texture contrast soils under varying soil moisture conditions.

#### 5.1.2 *Irrigation scheduling*

Irrigation scheduling of crops is often undertaken with moisture stress on the crop as the deciding factor. Avoiding crop moisture stress is ideal method of irrigation scheduling particularly when there is ample irrigation for the season. However, when crops such as cereals receive limited irrigation due to precedence of other higher value crops or limited water availability, irrigation scheduling becomes critical. Often the available water is applied when the crop is most likely already under moisture stress, which occurs in the warmer spring months. However, this is when the cracks that lead to loss of irrigation through deep drainage as described by Greve *et al.* (2010). Applying water before cracks have formed in vertic soil is a potential method of overcoming this problem, however it is counterintuitive in a farming system. This may be the ideal method to maintain favourable soil conditions for optimum root growth but it does not encourage the plant to search for water as soil moisture is readily available. This is where a balance of encouraging root growth without causing moisture stress becomes a strategic management tool. Figure 5-1 illustrates how irrigation could be used to make cracks advantageous in improving root exploration. At high soil moisture, soil strength is reduced. As soil dries, soil strength

increases, which impacts on root growth. However, further reduction of soil moisture leads to crack formation creating pathway for root exploration. This may allow access to the soil matrix within the peds via the crack wall. However, this is dependent on the penetration resistance of the crack face. Once the cracks have formed, strategic irrigation may be used to provide periods of favourable conditions for root growth into the soil matrix. When cracks appear, this gives the roots another method for growth deeper into the profile. Early season irrigation slows down the development and severity of cracking, which means that further irrigation or rainfall is less likely to be lost via deep drainage, becomes absorbed into the soil peds and remains in the root zone. The added benefit of maximising root growth earlier in the season means that deeper root depth leads roots to access subsoil moisture that may have not been available later in the season when crop moisture stress is at its greatest.

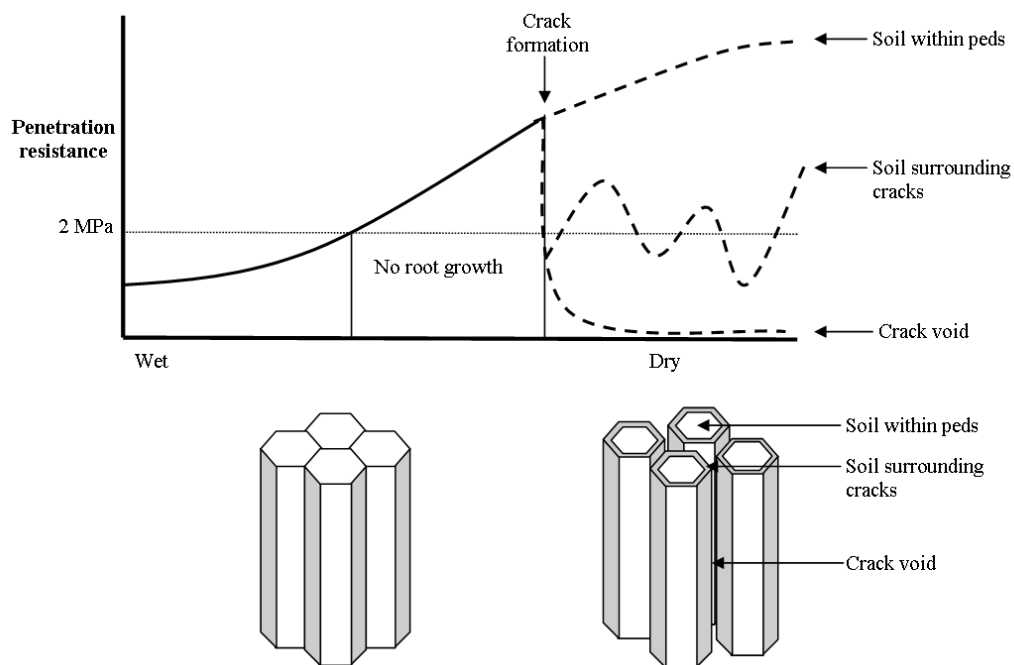


Figure 5-1. A conceptual hypothesis on the dynamic relationship between shrink swell soils and root growth.

Chapter 3 demonstrated that cracks in the surrounding soil matrix play an important role in root proliferation. Figure 5-1 conceptualises how roots may be affected by high soil strength and crack formation. In a wet soil there are no cracks and root growth is not severely limited by high soil strength. Yet as the soil dries, soil strength increases, which begins to impede root growth. However, as the soil continues to dry the formation of shrinkage cracks creates planes of weakness in the soil into which the roots can grow. Pankhurst *et al.* (2002) stated that 80% of roots can be confined to cracks resulting in decreased water uptake. However, the dynamic nature of shrinkage crack formation in vertic soils may confine root growth, but when moisture infiltrates the crack and reduce penetration resistance of face of the crack it may improve the abundance of roots within the soil matrix. The balance of soil moisture and crack formation in vertic soils minimises deeper cracks and therefore the loss of water through deep drainage.

### 5.1.3 *Crop simulation modelling of root growth*

The range of physical complexities in vertic texture contrast soils raised the question of how these soils perform under crop models that rely on the simplification of the soil-root system. APSIM module logic that simulates root growth overestimated the rate at which roots grew in these soils in comparison to barley under conditions of moisture or waterlogging stress. Simulations of barley grown under optimum vertic soil conditions matched observed root growth rates however, the rate of water extraction from the soil was overestimated, which lead to an overestimation of leaf area index across all three treatments. Changing the module logic to account for the effect of soil characteristics such as high penetration resistance and waterlogging improved the prediction of yield but highlighted

another issue, poor simulation of yield components. APSIM overestimated grain number and underestimated grain weight compared with observed results from field trials across three seasons. However, the changes to the root parameters in APSIM that improved the accuracy of simulated yield conversely exacerbated the disparity of yield components in both the simulated and observed results. The underlying cause appears to be the early and accelerated development of LAI by the model. As the simulation progressed with the season, the resulting crop components such as tiller number and stem weight are poorly simulated, leading to over-allocation of assimilates to yield components, namely grain weight.

One of the limitations of the field data was that it was for a single site and season. APSIM simulations can be run over extended time periods to account for seasonal differences. Modification of the APSIM root parameters can be extended over 50 years to capture the impact of seasonal variation. Early season irrigation had set irrigation parameters to reproduce the irrigation strategy set in the optimum treatment. The late season irrigation simulations replicated a common irrigation practice of applying water later in the season when the barley crop is more susceptible to moisture stress. Simulated yields in Figure 5-2 with the default root parameters over the 50 year simulation appeared unrealistically high when compared with the mean of 4.5 t/ha from historical trials conducted in Tasmania from 1975 to 2010. As demonstrated in Chapter 4, the default KL and XF parameters lead to excess root growth rate and hence depth, which inflated yield. Therefore the exaggerated root growth buffered any effect that irrigation scheduling had on crop yield. Including the modified KL and XF parameters in the model improved the prediction of yield, similar to historic levels.

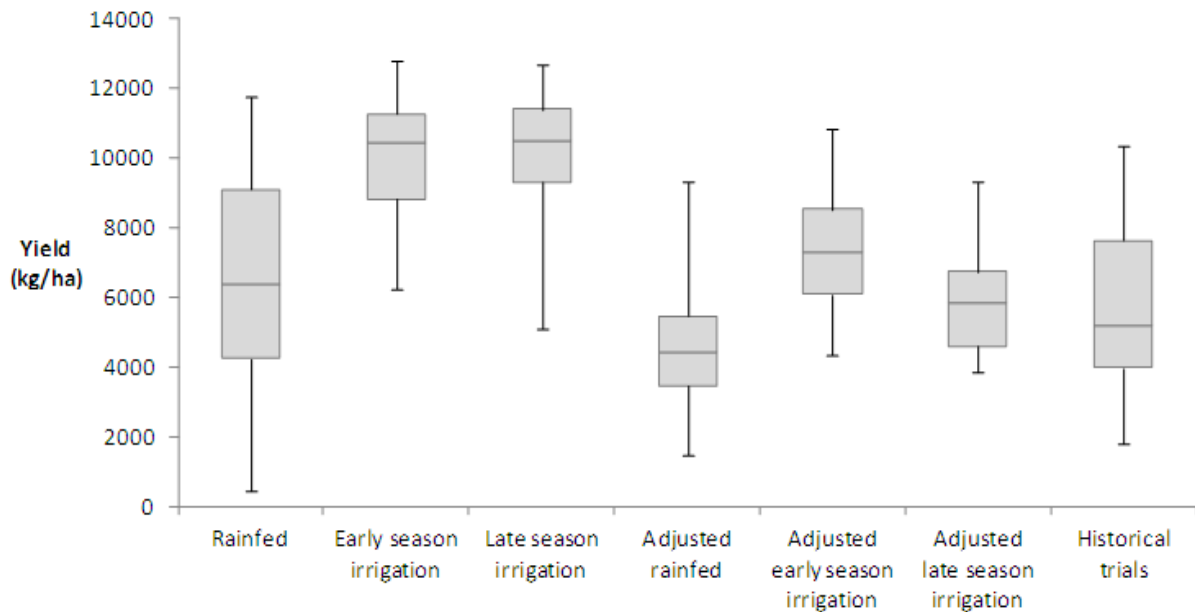


Figure 5-2. Yield of 50 year barley simulations from 1960 to 2010 in the Cambridge region containing default KL and XF parameters and adjusted parameterisations as pretested in the 2010/11, chapter 4. Simulations involved rainfed crops, early season irrigation, which consisted of irrigating when extractable soil water dropped below 140 mm between Zadok stage 1 and 45 and the late season simulation between Zadok stage 45 and 70.

Furthermore, the long term simulations can be used to determine the impact on WUE, therefore bringing together the aim of the thesis with modifications of the root parameters in APSIM. For example, simulated WUE over multiple years adjusted for root parameters ranged from 15.4 – 21 kg/ha.mm (Table 5-1). Similar to experiment results in Chapter 2, adjustments to KL and XF parameters reduced average WUE values within the range reported in barley by Botwright Acuña *et al.* (2010). The APSIM modelling over a 50 year period demonstrated that early irrigation was better than rainfed and late season irrigation for yield and WUE with adjusted root parameters. Greater root density and depth as a result of early irrigation increased overall water uptake and reduced deep drainage. However, using drained upper limit as an indication of perched water-table leading to waterlogging, early irrigation was more risk to waterlogging than a late irrigation regime. The APSIM modelling over a 50 year period demonstrated that early irrigation was better than rainfed and late season irrigation for yield and WUE with adjusted root parameters.

Table 5-1. Median values of WUE from 50 year barley simulations from 1960 to 2010 in the Cambridge region containing default KL and XF parameters and adjusted parameterisations as pretested in the 2010/11 trial, chapter 4. Simulations involved rainfed crops, early season irrigation, which consisted of irrigating when extractable soil water dropped below 140 mm between Zadok stage 1 and 45 and the late season simulation between Zadok stage 45 and 70. Simulation outputs included plant water uptake and water loss from the cropping system. Day of soil moisture being greater than the drained upper limit (DUL) occurring in the soil layer above the B horizon was used to determine the prevalence of perched waterlogging.

	Rainfed	Early season irrigation	Late season irrigation	Adjusted rainfed	Adjusted early season irrigation	Adjusted late season irrigation
Days above DUL	16	35	31	16	29	21
Runoff	3	4	4	4	4	4
Drainage	11	22	18	35	33	40
Soil evaporation	128	133	127	133	133	133
Plant water uptake	167	247	251	117	177	140
Total water use (mm)	310	406	400	289	346	317
Yield (kg/ha)	6410	10441	10506	4440	7286	5819
WUE (kg/ha.mm)	20.6	25.7	26.3	15.4	21.0	18.3

#### 5.1.4 *Future experiments*

This thesis, through horizontal excavation of soil, gave a detailed analysis of how vertically growing roots interacted with physical soil characteristics with depth. However, this approach did not allow the comprehensive examination of roots that grew horizontally into the soil matrix. Results demonstrated that cracks influenced root growth into the soil matrix via the crack wall, yet more detailed in situ analysis is required to better understand the role of shrinkage cracks in root proliferation.

Waterlogging is difficult to quantify in texture contrast soil due to perched waterlogging on the top of the B horizon. Lysimeters are often used to monitor evapotranspiration and deep drainage in soils. Installation of shallow lysimeters on the top of the B horizon under varied irrigation regimes may give a more accurate representation of occurrence and length



of waterlogging. This data could be used to better simulate waterlogging in APSIM simulations, and parameterise the infiltration of water into the B horizon, leading to greater accuracy to simulated water movement.

Future research requires a more detailed analysis of the relationships between root growth and the soil characteristics. Laboratory experiments that evaluate the relationship between soil moisture, soil strength and crack formation in vertic soils that lead to a greater understanding of when and how cracks form, i.e. a slow or sudden release of peds. In addition, a function could be developed by which APSIM can simulate formation of cracks within a soil layer based on the changes in soil moisture over the growing season rather than just bulk density and particle size. This could potentially improve how APSIM simulates water movement within vertic texture contrast soils by taking into account preferential pathways using a multiple pore domain model where water can bypass a layer, rather than the simple tipping bucket method in which water moved to the next soil layer once it has reached field capacity.

#### 5.1.5 *Conclusion*

Texture contrast soils occupy approximately 20% of Australia (Chittleborough 1992) and roughly 80% of Southern Australian agricultural regions (Stevens *et al.* 1999) and play an important role for agriculture to meet the nutritional demand of a growing population. Texture contrast soils have been regarded as difficult soil to crop and this view is shared by growers within Tasmanian cropping regions and that annual crops only utilise the upper 30 – 40 cm of the soil (Gunn *et al.* 2010, pers. comm.). However, when appropriately managed, texture contrast soils have demonstrated to be no less productive compared with

many other soils (Anderson *et al.* 1992). A greater understanding of soil physical characteristics and soil/root interactions can improve root growth through strategic irrigation can be achieved by either encouraging root elongation through shrinkage cracks at low moisture content, or encouraging root elongation through the soil matrix at higher soil moisture content essentially, irrigating the soil not the plant. The complexities of vertic texture contrast soils are highlighted when modelling crop performance on these soils. The assessment of APSIM of barley grown in these soils demonstrates improvements are required when simulation of crop physiology under Tasmanian conditions and root/soil interactions particularly under texture contrast or vertic soils. Adaptations to the model are able to account for the complications but a more dynamic system needs to be developed.

## 6.0 References

- ABS (2004). *1384.6 - Statistics - Tasmania, 2005*. Canberra: Australian Bureau of Statistics.
- ABS (2008). Australian Bureau of Statistics- Agricultural State Profile, Tasmania, 2004-05.
- Alcamo J, Henrichs T & Rosch T (2000). *World Water in 2025. Global modeling and scenario analysis for the World Commission on Water for the 21st Century*. Kassel: University of Kassel
- Amoozegar A & Warrick AW (1986). Hydraulic conductivity of saturated soils: field methods. In *Methods of Soil Analysis: Part 1-Physical and Mineralogical Methods*, Vol. Agronomy monograph No. 9, 735-770 (Ed Klute A). Madison, WI: American Society of Agronomy Soil Science Society of America.
- Anderson PM, Oelke EA & Simmons SR (2002). Growth and Development Guide for Spring Barley University of Minnesota.
- Anderson WK, French RJ & Seymour J (1992). Yield responses of wheat and other crops to agronomic practices on duplex soils compared with other soils in Western Australia. *Australian Journal of Experimental Agriculture* 32: 963-970.
- Anderson WK & Garlinge JR (2000). *The wheat book: principles and practice*. South Perth, Western Australia: Department of Agriculture.
- Angus JF & Herwaarden AF (2001a). Increasing water-use and water use efficiency in dryland wheat. *Agronomy Journal* 93: 290-298.
- Aspinall D, Nicholls PB & May LH (1964). The effects of soil moisture stress on the growth of barley I. Vegetative development and grain yield. *Australian Journal of Agricultural Research* 15: 729-745.
- Bates BC, Kundzewicz ZW, Wu S & Palutikof JP (2008). *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland.
- Beal A (1993). Dryland salinity management in the Murray-Darling Basin. *Murray-Darling Basin Commission*.
- Belford RK, Dracup M & Tennant D (1992). Limitations to growth and yield of cereal and lupin crops on duplex soils. *Australian Journal of Experimental Agriculture* 32: 929-945.
- Berry PM, Sterling M, Spink JH, Baker CJ, Sylvester-Bradley R, Mooney SJ, Tams AR & Ennos AR (2004). Understanding and reducing lodging in cereals. *Advances in Agronomy* 84: 217-271.

- Botwright Acuña T, Dean DJ & Riffkin P (2011). Constraints to achieving high potential yield of wheat in a temperate, high-rainfall environment in south-eastern Australia. *Crop and Pasture Science* 62: 125-136.
- Botwright Acuña T, Lisson S, Johnson P & Dean G (2015). Yield and water-use efficiency of wheat in a high-rainfall environment. *Crop and Pasture Science* 66: 419-429.
- Botwright Acuña T, O'Leary G & Riffkin P (2010). Effect of time of sowing on phenology of cereals grown in a temperate environment in south-eastern Australia. In *15th Australian Agronomy Conference* (Eds Dove H and Culvenor RA). Lincoln, New Zealand.
- Caierão E (2006). Effect of induced lodging on grain yield and quality of brewing barley. *Crop Breeding and Applied Biotechnology* 6: 215-221.
- Carberry PS, Adiku SGK, McCown RL & Keating BA (1995). Application of the APSIM cropping systems model to intercropping systems. In *Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics*, Vol. 3, 637-648 (Eds Osamu I, Johansen C, Adu-Gyamfi JJ, Katayama K, Rao JVDKK and Rego TJ). JIRCAS International Agriculture Series.
- Carberry PS, Hochman Z, Hunt RJ, Dalgliesh NP, McCown RL, Whish JPM & Robertson MJ (2009). Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops. *Crop and Pasture Science* 60: 1044-1056.
- Chartres C & Williams J (2006). Can Australia overcome its water scarcity problems? *Journal of Developments in Sustainable Agriculture* 1: 17-24.
- Chen C, Roseberg R & Selker J (2002). Using microsprinkler irrigation to reduce leaching in a shrink/swell clay soil. *Agricultural Water Management* 54: 159-171.
- Chittleborough DJ (1992). Formation and pedology of duplex soils. *Australian Journal of Experimental Agriculture* 32: 815-825.
- Clark LJ, Whalley WR & Barraclough PB (2003). How do roots penetrate strong soil? *Plant and Soil* 255: 93-104.
- Clough A, Riffkin PA, Harris RH, Nuttall J & O'Leary GJ (2010). Providing high rainfall zone growers with confidence in new and alternative management practices. In *The 15th Australian Agronomy Conference* (Eds Dove H and Culvenor RA). Lincoln, New Zealand.
- Connolly RD, Bell M, Huth N, Freebairn DM & Thomas G (2002). Simulating infiltration and the water balance in cropping systems with APSIM-SWIM. *Soil Research* 40(2): 221-242.
- Cotching WE, Lynch S & Kidd BD (2009). Dominant soil orders in Tasmania: distribution and selected properties *Australian Journal of Soil Research* 47: 537-548.

- Crook MJ & Ennos AR (1994). Stem and root characteristics associated with lodging resistance in four winter wheat cultivars. *The Journal of Agricultural Science* 123: 167-174.
- Da Silva AP & Kay BD (1997). Estimating the least limiting water range of soils from properties and management. *Soil Science Society of America Journal* 61: 877-883.
- Day AD & Dickson AD (1958). Effect of artificial lodging on grain and malt quality of fall-sown irrigated barley. *Agronomy Journal* 50: 338-340.
- Dean GJ (2001). Production of legume forage crops in frost-prone areas of Tasmania. In *The 10th Australian Agronomy Conference*. (Eds Rowe B, Donaghy D and Mendham N). Hobart, Tasmania.
- Dean GJ & Mendham NJ (2001). Agronomic and economic potential of grain legumes in Tasmania. In *The 10th Australian Agronomy Conference*. (Eds Rowe B, Donaghy D and Mendham N). Hobart, Tasmania.
- Dexter AR (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* 120: 201-214.
- Döös BR (1994). Environmental degradation, global food production, and risk for large-scale migrations *Ambio* 23: 124-130.
- DPIW (2008). DPIW- Industry profile- Cereals.
- DPIWE (2004). *Tasmanian Rural and Marine Industry Profiles 2004*. Department of Primary Industries, Water and Environment
- Dracup M, Belford RK & Gregory PJ (1992). Constraints to root growth of wheat and lupin crops in duplex soils. *Australian Journal of Experimental Agriculture* 32: 947-961.
- Eadie L & Stone C (2012). *Farming smarter, not harder: Securing our agricultural economy*. Sydney, NSW Centre for Policy Development: Centre for Policy Development (Sydney, N.S.W.)
- Eagles HA, Bedgood AG, Panozzo JF & Martin PJ (1995). Cultivar and environmental effects on malting quality in barley. *Australian Journal of Agricultural Research* 46: 831-844.
- Edwards I (1992). Farming duplex soils: a farmer's perspective. *Australian Journal of Experimental Agriculture* 32: 811-814.
- Evans LT & Fischer RA (1999). Yield potential: Its definition, measurement, and significance. *American Society of Agronomy* 39: 1544-1551.
- Fischer RA (1985). Number of kernels in wheat crops and the influence of solar radiation and temperature. *The Journal of Agricultural Science* 105: 447-461.

- French RJ & Schultz JE (1984a). Water-use efficiency of wheat in a Mediterranean-type environment. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* 35: 743-764.
- French RJ & Schultz JE (1984b). Water use efficiency of wheat in a Mediterranean-type environment. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* 35: 743-764.
- Gallagher JN, Biscoe PV & Scott RK (1976). Barley and its environment: VI. Growth and development in relation to yield. *Journal of Applied Ecology* 13(2): 563-583.
- García del Moral LF, Ramos JM, García del Moral MB & Jiménez-Tejada MP (1991). Ontogenetic approach to grain production in spring barley based on path-coefficient analysis. *Crop Science* 31: 1179-1185.
- Gardner WK, Fawcett RG, Steed GR, Pratley JE, Whitfield DM & van Rees H (1992). Crop production on duplex soils in south-eastern Australia. *Australian Journal of Experimental Agriculture* 32: 915-927.
- Giunta F, Motzo R & Deidda M (1993). Effect of drought on yield and yield components of durum wheat and triticale in a Mediterranean environment. *Field Crops Research* 33: 399-409.
- Gracia C, Alemany E & Bautista I (2012). Relationship among compaction, moisture and penetration resistance in horticultural soil. In *International Conference of Agricultural Engineering*. Valencia, Spain.
- Gregory PJ, Tennant D & Belford RK (1992). Root and shoot growth, and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a Mediterranean-type environment. *Australian Journal of Agricultural Research* 43: 555-573.
- Greve A, Andersen MS & Acworth RI (2010). Investigations of soil cracking and preferential flow in a weighing lysimeter filled with cracking clay soil. *Journal of Hydrology* 393: 105-113.
- Gyles OA, Smith CJ, Wilson IB & Pritchard KE (1987). Response of barley to nitrogen and irrigation. In *Proceedings Australian Barley Technical Symposium*. Wagga Wagga, New South Wales.
- Hamblin A & Tennant D (1987). Root length density and water uptake in cereals and grain legumes: How well are they correlated? *Australian Journal of Agricultural Research* 38: 513-527.
- Hardie MA, Cotching WE, Doyle RB, Holz G, Lisson S & Mattern K (2011). Effect of antecedent soil moisture on preferential flow in a texture-contrast soil. *Journal of Hydrology* 398: 191-201.

- Hardie MA, Doyle RB, Cotching WE, Mattern K & Lisson S (2012). Influence of antecedent soil moisture on hydraulic conductivity in a series of texture-contrast soils. *Hydrological Processes* 26: 3079-3091.
- Hazelton PA & Murphy BW (2007). *Interpreting soil test results: What do all the numbers mean*. CSIRO Publishing. Melbourne, Australia.
- Hoad SP, Russell G, Lucas ME & Bingham IJ (2001). The management of wheat, barley, and oat root systems. In *Advances in Agronomy*, Vol. 74, 193-246 San Diego: Academic Press Inc.
- Hochman Z, Holzworth D & Hunt RJ (2009). Potential to improve on-farm wheat yield and WUE in Australia. *Crop and Pasture Science* 60: 708-716.
- Holz GK (1994). Principles of soil occurrence in the lower Coal River Valley, South East Tasmania. In *Department of Agricultural Science*. Hobart: University of Tasmania
- Hunt J, van Rees H, Hochman Z, Carberry P, Holzworth D, Dalgliesh N, Brennan L, Poulton P, van Rees S, Huth N & Peake A (2006). Yield Prophet<sup>®</sup>: An online crop simulation service. In *13th Australian Agronomy Conference* (Eds Turner N and Acuna TB). Perth, Australia.
- Isbell RF (2002). *The Australian Soil Classification, Revised Edition*. Melbourne: CSIRO.
- Jabro JD, Leib BG & Jabro AD (2005). Estimating soil water content using site-specific calibration of capacitance measurements from Sentek EnviroSCAN systems. *Applied Engineering in Agriculture* 21: 393-399.
- Jamieson PD, Martin RJ & Francis GS (1995). Drought influences on grain yield of barley, wheat, and maize. *New Zealand Journal of Crop and Horticultural Science* 23: 55-66.
- Johnson IR, Chapman DF, Snow VO, Eckard RJ, Parsons AJ, Lambert MG & Cullen BR (2008). DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. *Australian Journal of Experimental Agriculture* 48: 621-631.
- Keating BA, Asseng S, Brown S, Carberry PS, Chapman SC, Dimes JP, Freebairn DM, Hammer GL, Hargreaves JNG, Hochman Z, Holzworth DP, Huth NI, Meinke H, McCown RL, Probert ME, Robertson MJ, Silburn DM, Smith CJ, Snow VO, Verburg K & Wang E (2003a). The Agricultural Production Systems Simulator (APSIM): its history and current capability. *European Journal of Agronomy and Crop Science* 18(3): 267-288.
- Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM & Smith CJ (2003b). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18: 267-288.

- Kirkegaard JA & Lilley JM (2007). Root penetration rate - a benchmark to identify soil and plant limitations to rooting depth in wheat *Australian Journal of Experimental Agriculture* 47: 590-602.
- Kirkegaard JA, Lilley JM, Howe GN & Graham JM (2007). Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* 58: 303-315.
- Lilley JM & Kirkegaard JA (2007). Seasonal variation in the value of subsoil water to wheat: simulation studies in southern New South Wales. *Australian Journal of Agricultural Research* 58: 1115-1128.
- MacEwan RJ, Crawford DM, Newton PJ & Clune TS (2010). High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. *Australian Journal of Soil Research* 48: 150–166.
- Manschadi AM, Christopher JT, deVoil P & Hammer GL (2006). The role of root architectural traits in adaptation of wheat to water-limited environments *Functional Plant Biology* 33: 823-837.
- Matuszek M (2009). Growth, yield and water-use efficiency of barley grown under irrigated and rainfed conditions. In *School of Agricultural Science* Hobart, Tasmania: University of Tasmania. Honours thesis.
- McCown RL, Hammer GL, Hargreaves JNG, Holzworth D & Huth NI (1995). APSIM: an agricultural production system simulation model for operational research. *Mathematics and Computers in Simulation* 39: 225-231.
- McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP & Freebairn DM (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural system research. *Agricultural Systems* 50: 255-271.
- McKenzie N, Coughlan K & Cresswell H (2002). *Soil physical measurement and interpretation for land evaluation*. CSIRO.
- Mendham DS (1994). Factors affecting the malting quality of barley. In *Department of Agriculture*, Vol. Bachelor of Agricultural Science degree with Honours. Hobart: University of Tasmania.
- Mendham NJ & Russell J (1986). In pursuit of higher wheat and triticale yields in Tasmania. In *Wheat breeding for high rainfall areas*. (Eds Gardner WK and O'Brien L). Victorian Crops Research Institute Horsham, Australia.
- Merdun H, Meral R & Riza Demirkiran A (2008). Effect of the initial soil moisture content on the spatial distribution of the water retention. *Eurasian Soil Science* 41: 1098-1106.



- Miralles DJ & Richards RA (2000). Responses of leaf and tiller emergence and primordium initiation in wheat and barley to interchanged photoperiod. *Ann Bot* 85(5): 655-663.
- Miralles DJ, Richards RA & Slafer GA (2000). Duration of the stem elongation period influences the number of fertile florets in wheat and barley. *Australian Journal of Plant Physiology* 27: 931-940.
- Mitchell A & van Genuchten M (1993). Flood irrigation of a cracked soil. *Soil Science Society of America Journal* 57: 490-497.
- National Water Commission (2013). *National Water Planning Report Card - Tasmania*. Canberra: Australian Government
- Northcote KH (1979). *A factual key for the recognition of Australian soils*. Adelaide: Rellim Technical Publications.
- Novák V, Šimůnek J & Van Genuchten MT (2002). Infiltration into a swelling, cracked clay soil. *Journal of Hydrology and Hydromechanics* 50: 3-19.
- O'Keeffe K & Fettell N (2010). *Barley varieties & sowing rates for irrigation*. Irrigation Research and Extension Committee
- Pankhurst CE, Pierret A, Hawke BG & Kirby JM (2002). Microbiological and chemical properties of soil associated with macropores at different depths in a red-duplex soil in NSW Australia. *Plant and Soil* 238: 11-20.
- Passioura JB (1983). Roots and drought resistance. *Agricultural Water Management* 7: 265-280.
- Passioura JB (1991). Soil structure and plant growth. *Australian Journal of Soil Research* 29: 717-728.
- Penning de Vries FWT & van Laar HH (1982). *Simulation of growth processes and the model BACROS*. Pudoc, Wageningen.
- Perry MW (1987a). Water-use efficiency of non-irrigated field crops. In *Agronomy 1987-response to change. Proceedings of the 4th Australian Agronomy Conference* La Trobe University, Melbourne: The Australian Society of Agronomy.
- Perry MW (1987b). Water use efficiency of non-irrigated field crops. In *Agronomy 1987-response to change. Proceedings of the 4th Australian Agronomy Conference* The Australian Society of Agronomy La Trobe University, Melbourne.
- Pook MJ (2001). *Tasmania's climate and projections for the century*. Hobart: Department of Primary Industries and Water.
- Richardson AEV (1923). The water requirements of farm crops. Influence of environment on the transpiration ratio. *Journal of the Department of Agriculture Victoria* 21: 193-284.

- Robertson MJ & Kirkegaard JA (2005). Water-use efficiency of dryland canola in an equi-seasonal rainfall environment. *Australian Journal of Agricultural Research* 56: 1373-1386.
- Robson AD, Longnecker NE & Osborne LD (1992). Effects of heterogeneous nutrient supply on root growth and nutrient uptake in relation to nutrient supply on duplex soils. *Australian Journal of Experimental Agriculture* 32: 879-886.
- Römken MJM & Prasad SN (2006). Rain infiltration into swelling/shrinking/cracking soils. *Agricultural Water Management* 86: 196-205.
- Russell J & Mendham NJ (1985a). *The effect of time of planting on the yield of Triumph barley, Bindawarra wheat and Coorong triticale*. Project report.
- Russell J & Mendham NJ (1985b). *Response of barley to Irrigation and Nitrogen*. Project report.
- Ruuska SA, Rebetzke GJ, van Herwaarden AF, Richards RA, Fettell NA & Tabe L (2006). Genotypic variation in water-soluble carbohydrate accumulation in wheat. *Functional Plant Biology* 33: 799-809.
- Sadras O & Angus JF (2006a). Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* 57: 847-856.
- Sadras V, Baldock J, Roget D & Rodriguez D (2003). Measuring and modelling yield and water budget components of wheat crops in coarse-textured soils with chemical constraints. *Field Crops Research* 84: 241-260.
- Sadras VO & Angus JF (2006b). Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* 57: 847-856.
- Salim MH, Todd GW & Schlehuber AM (1965). Root development of wheat, oats and barley under conditions of soil moisture stress. *Agronomy Journal* 57: 603-607.
- Shaffer MJ, Gupta SC, Linden DR, Molina JAE, Clapp LE & Larson WE (1983). Simulation of nitrogen, tillage, and residue management effects on soil fertility. In *Analysis of ecological systems: State-of-the-art in ecological modelling* (Eds Lauenroth WK, Skogerboe GV and Flug M). New York: Elsevier.
- Siddique KHM, Belford RK & Tennant D (1990). Root:shoot ratios of old and modern, tall and semi-dwarf wheats in a Mediterranean environment. *Plant and Soil* 121: 89-98.
- Simane B, Struik PC, Nachit MM & Peacock JM (1993). Ontogenetic analysis of yield components and yield stability of durum wheat in water-limited environments. *Euphytica* 71: 211-219.
- Šimůnek J, Sejna M & van Genuchten MT (1999). *The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in*

*variably-saturated media. version 2.0.* Salinity Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Riverside, California

- Sinclair TR, Tanner CB & Bennett JM (1984). Water-use efficiency in crop production. *BioScience* 34: 36-40.
- Sisler WW & Olson PJ (1951). A study of methods of influencing lodging in barley and the effect of lodging upon yield and certain quality characteristics. *Scientific Agriculture* 31: 117-186.
- Spragg J (2014). *Australian feed grain supply and demand report 2013/14*. Berwick, Victoria: Feed Grain Partnership.
- Stevens DP, Cox JW & Chittleborough DJ (1999). Pathways of phosphorus, nitrogen and carbon movement over and through texturally differentiated soils, South Australia. *Australian Journal of Soil Research* 37: 679-693.
- Stewart LK, Charlesworth PB, Bristow KL & Thorburn PJ (2006). Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. *Agricultural Water Management* 81(3): 315-334.
- Stockle CO, Martin S & Campbell GS (1994). CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agricultural Systems* 46: 335-359.
- Strobl C, Malley J & Tutz G (2009). An introduction to recursive partitioning: Rationale, application and characteristics of classification and regression trees, bagging and random forests. *Psychological Methods* 14: 323-348.
- Strong WM, Dalal RC, Weston EJ, Lehane KJ, Cooper JE, King AJ & Holmes CJ (2006). Sustaining productivity of a Vertosol at Warra, Queensland, with fertilisers, no-tillage or legumes. 9. Production and nitrogen benefits from mixed grass and legume pastures in rotation with wheat. *Australian Journal of Experimental Agriculture* 46: 375.
- Tao F, Yokozawa M, Xu Y, Hayashi Y & Zhang Z (2006). Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agricultural and Forest Meteorology* 138: 82-92.
- Tennant D, Scholz G, Dixon J & Purdie B (1992). Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture* 32: 827-843.
- Ticehurst JL, Cresswell HP, McKenzie NJ & Gloverc MR (2007). Interpreting soil and topographic properties to conceptualise hillslope hydrology. *Geoderma* 137: 279-292.
- Turner NC (1992). Crop production on duplex soils: an introduction. *Australian Journal of Experimental Agriculture* 32: 797-800.

- Turtola E & Paanjanen A (1995). Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. *Agricultural Water Management* 28: 295-310.
- van Noordwijk M, Brouwer G, Meijboom F, Oliveira MG & Bengough AG (2000). Trench profile techniques and core break methods. In *Root Methods: A Handbook*, 211-233 (Eds Smit AL, Bengough AG, Engels C, Noordwijk Mv, Pellerin S and Geijn SCvd). Berlin, New York: Springer-Verlag.
- Wang E & Engel T (1998). Simulation of phenological development of wheat crops *Agricultural Systems* 58: 1-24.
- Wang W & Smith CJ (2004). Modelling the growth and water uptake function of plant root systems: a review. *Australian Journal of Agricultural Research* 55: 501-523.
- Watt M, Silk WK & Passioura JB (2006). Rates of root and organism growth, soil conditions, and temporal and spatial development of the rhizosphere. *Ann Bot* 97: 839-855.
- Weaver T, Hulugalle N & Ghadiri H (2005). Comparing deep drainage estimated with transient and steady state assumptions in irrigated vertisols. *Irrigation Science* 23(4): 183-191.
- Whalley WR, Clark LJ, Gowing DJG, Cope RE, Lodge RJ & Leeds-Harrison PB (2006). Does soil strength play a role in wheat yield losses caused by soil drying? *Plant and Soil* 280: 279-290.
- White RG & Kirkegaard JA (2010). The distribution and abundance of wheat roots in a dense, structured subsoil – implications for water uptake. *Plant, Cell and Environment* 33: 133-148.
- Whiteley GM & Dexter AR (1983). Behaviour of roots in cracks between soil peds. *Plant and Soil* 74: 153-162.
- Whitmore AP & Whalley WR (2009). Physical effects of soil drying on roots and crop growth. *J Exp Bot* 60: 2845-2857.
- Williams JR, Jones CA & Dyke PT (1984). A modeling approach to determining the relationship between erosion and soil productivity [EPIC, Erosion-Productivity Impact Calculator, mathematical models]. *American Society of Agricultural Engineers* 27: 129-144.
- World Bank (2008). *World Development Report 2008*. Washington, DC: © World Bank. <https://openknowledge.worldbank.org/handle/10986/5990> License: CC BY 3.0 IGO
- Zadoks JC, Chang TT & Konzak CF (1974). A decimal code for the growth stages of cereals. *Weed Research*: 415-421.

- Zhang H, Turner NC & Poole ML (2005). Water use of wheat, barley, canola, and lucerne in the high rainfall zone of south-western Australia. *Australian Journal of Agricultural Research* 56: 743-752.
- Zhang H, Turner NC, Poole ML & Asseng S (2007). High ear number is key to achieving high wheat yields in the high-rainfall zone of south-western Australia. *Australian Journal of Agricultural Research* 58: 21-27.
- Zhang H, Turner NC, Poole ML & Simpson N (2006). Crop production in the high rainfall zones of southern Australia — potential, constraints and opportunities. *Australian Journal of Agricultural Research* 46: 1035-1049.
- Zobel RW (2005). Primary and secondary root systems. In *Roots and soil management: interactions between roots and the soil*. (Eds Zobel RW and Wright SF). Beaver, West Virginia: American Society of Agronomy.